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ARCTIC ENVIRONMENT STUDY

FINAL REPORT

OCTOBER 1969

AEROSPACE GROUP
THE BOEING COMPANY
SEATTLE, WASHINGTON

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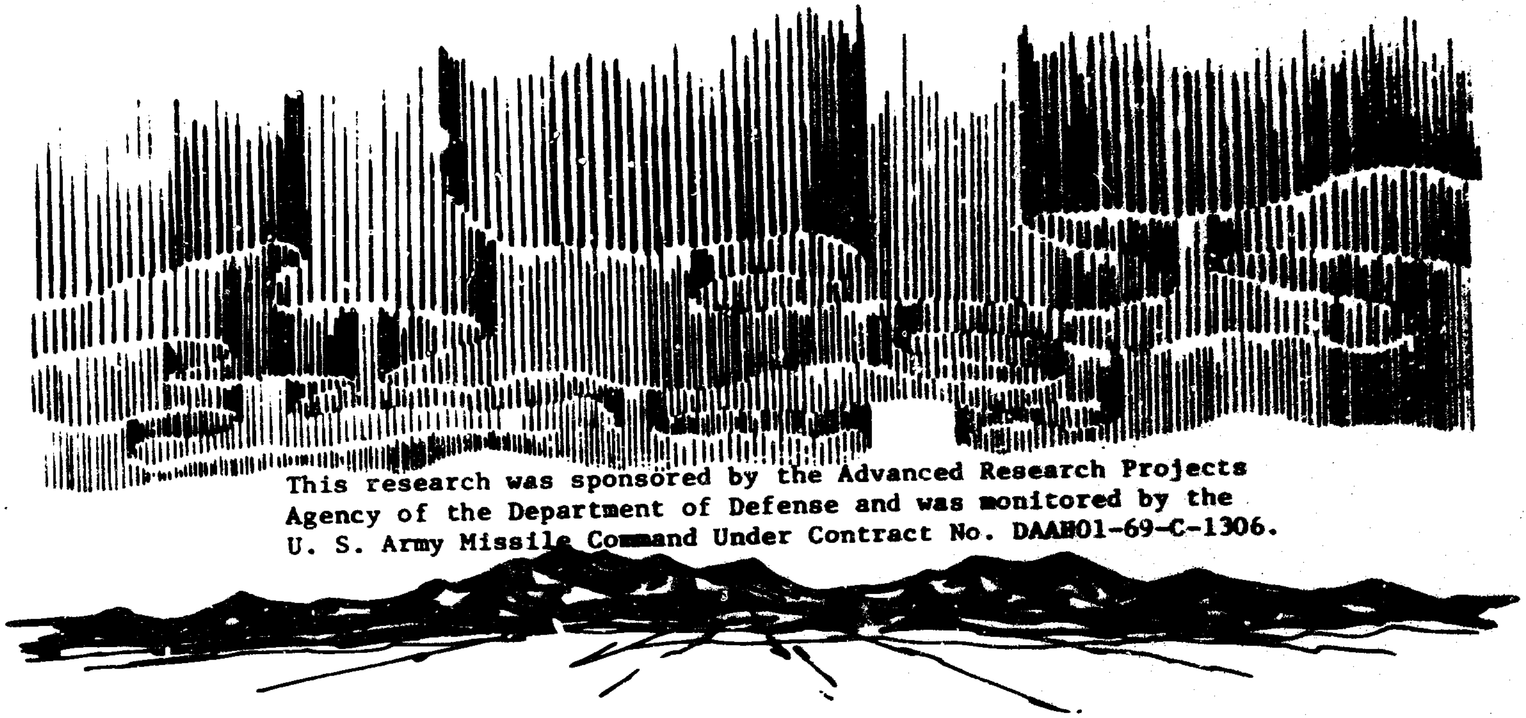

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ARCTIC ENVIRONMENT STUDY

FINAL REPORT

Sponsored by:

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ABSTRACT

The arctic environment has been investigated with emphasis placed on gathering data that impact vehicle and system operation over, on, and under the arctic ice pack. The area considered was restricted to the Arctic Ocean and contiguous seas. Included are descriptions of the arctic ice pack, ice mechanics, oceanography, and climatolcgy as well as details of the rationale employed in making a determination of the specific aspects of the environment to be considered. Deficiencies in presently available data in the U.S. and Canada are discussed.

KEY WORDS

Arctic
Environment
Oceanography
Climatology
Sea Ice
Arctic Ocean
Polar Ice
Arctic Basin
Ice Topography
Mobility
Vehicles

SUMMARY

The purpose of this study has been to identify and to gather available information on those aspects of the arctic environment pertinent to the evaluation of various vehicles and systems that might be utilized in the Arctic Basin.

During the study persons and organizations throughout both the military and civilian arctic community were contacted to obtain data and to establish potential sources of data.

Five types of vehicles were considered as potential candidates for operation in the arctic: (1) aircraft; (2) air cushion; (3) land; (4) ships and captured-air bubble; and (5) submarines. Land vehicles were dropped from consideration when it was found that the ice conditions were such that the mobility for large sizes was seriously limited. Investigation of the environment concentrated on the portions of the environment that would affect these systems. This included ice mechanics, character of the polar ice pack, climatology, and certain aspects of Arctic Ocean oceanography. It was not the intent of this study to evaluate the impact of the environment on specific vehicles or systems, although limitations imposed by ice conditions on land vehicles and ships are obvious and were treated accordingly.

There is little point in attempting to summarize the environmental information contained in this report since it only becomes meaningful when applied in the context of a particular system. It is worthwhile, however, to summarize conclusions regarding the state of knowledge of the arctic and more particularly the Arctic Basin. These are discussed in more detail in Section 4.0. Specific problem areas are discussed in each environmental section (Sections 5.0 through 9.0).

Knowledge of the arctic areas where human habitation exists is generally well known, but outside these areas one finds little more than random scientific investigations of short duration and limited scope. The most extensive investigations on a geographic basis have been those conducted by the Naval Oceanographic Office Birds Eye flights and the nuclear submarine operations under the ice pack. The former are fairly extensive, but accuracy suffers from a serious lack of adequate ice measurement instrumentation. The submarine operations provide the most useful data, but geographic coverage is limited and very little of the existing operations are available due to lack of processing and for security reasons.

The basic problem behind the lack of information on the Arctic Basin is a lack of national interest in the area. A justification of expenditures of funds to carry on the required geographic and seasonal studies will only be made when a military or commercial use is identified.

At present, it appears that even modest expenditures of money for instrumentation and manpower to obtain and process the data would result in a considerable increase in knowledge, particularly in regard to the polar ice pack, which is the dominant environmental feature of the basin.

The user of the data compiled in this report is cautioned that the information in many cases is based on meager and often questionable measurements and observations. As in the processing of any environmental data, extrapolation and averaging in both time and by area is utilized. In many instances in this report it has been impossible to determine valid extreme conditions since sufficient information is not available to derive reliable statistical values.

1.0 INTRODUCTION

1.0 PURPOSE OF STUDY

The operation of man and machines in the arctic polar area has been of minor concern until recently. However, with the growing recognition of the military and commercial potentials of this area it is increasingly evident that serious study must be given to understand the arctic environment. This study, therefore, has been limited to gathering available information on those aspects of the arctic environment pertinent to the evaluation of various vehicles and associated systems that might be considered for use in the Arctic Basin.

1.2 SCOPE OF THE STUDY

Since there has been considerable research and investigation into the operation of vehicles and equipment in the land areas of the arctic, the study was restricted to the Arctic Ocean and the contiguous seas (Figure 1-1). Within this geographical area, the three major divisions of the environment investigated were:

1) Physical, geographic, and mechanical characteristics of the arctic ice pack;

2) Climatology;

3) Selected oceanographic characteristics.

Within each of these areas, investigation was restricted to specific phenomena identified as having a potential impact on the operation of vehicles and systems.

1.3 ORGANIZATION OF REPORT

The report is divided into two parts. Sections 1.0 through 4.0 establish the rationale and requirement for the various environmental parameters that are of concern to the various vehicles and systems. A general description of the arctic is also included to establish a background for the detail environmental sections.

Sections 5.0 through 9.0 compile the environment description by major elements. As an aid to persons concerned with vehicle or system operation, this environmental data is correlated with specific needs by means of a series of matrix charts that relate vehicle operation to appropriate aspects of the environment.

Each section contains its own references and glossary.

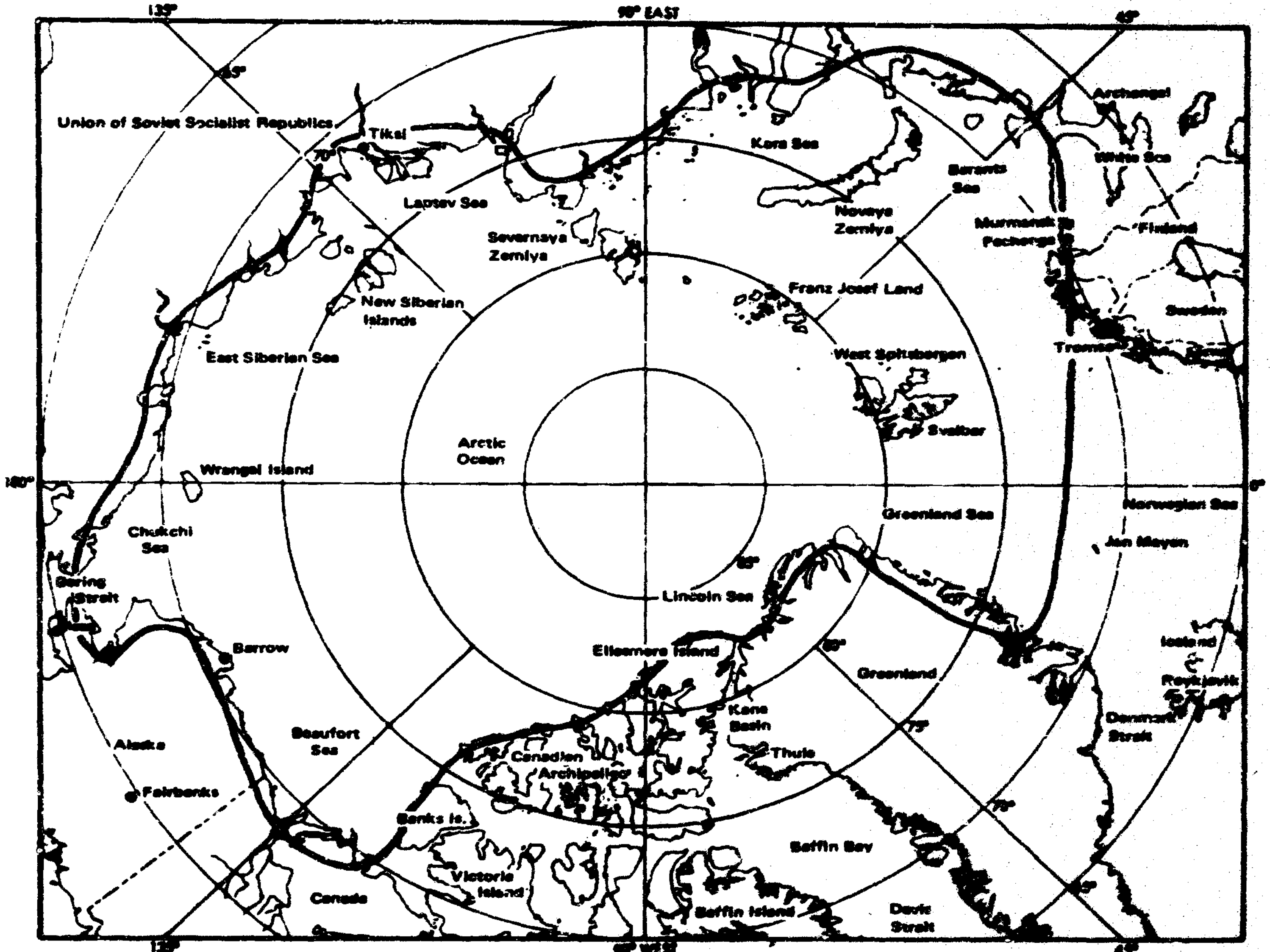


Figure 1-1: AREA OF STUDY (ARCTIC OCEAN)

2.0 THE ARCTIC REGION

The north polar region may be defined as that northern area of the earth beyond which the sun remains above the horizon for the whole midsummer day. This actually defines the area encompassed by the Arctic Circle at 60° 33' 03" north latitude. This area is predominated by ice, snow, and permafrost. It can be defined as one having less than 50 days between frosts, or an area north of which no trees will grow. It might also be called the region of mirages, increased visual and auditory perception, glare, fog, and the aurora borealis. In effect the arctic region is defined on the basis of climatic effects. The arctic to the oceanographer is dominated by the Arctic Ocean and includes in addition all of the contiguous water areas and islands.

A more meaningful definition of the arctic region encompasses the land area surrounding the North Pole and extending to the southern limit of continuous permafrost, the Arctic Ocean and adjacent waters. This region covers about 6.2 million square miles of which about 2.25 million square miles is permafrost land in Canada, Alaska, Siberia, and Greenland. Besides this area on the continents there are numerous groups of islands in the Arctic Ocean. The majority of these islands are north of the Eurasian continent and include Wrangel Island, New Siberian Islands, Severnaya Zemlya, Franz Josef Land, and Svalbard as well as many smaller islands. The Canadian Archipelago constitutes both the largest area and greatest number of islands in the arctic area.

The Arctic Ocean covers some 3,945,000 square miles; approximately three times the area of the Mediterranean Sea. This ocean is an arm of the North Atlantic Ocean, but is connected to the Pacific through the Bering Strait, a narrow shallow passage about 130 feet deep maximum, between North America and Asia. Bordering the Eurasian continent a series of relatively shallow seas over the continental shelf are directly contiguous to the Arctic Ocean or roughly separated by the islands. These include the Chukchi, East Siberian, Laptev, and Kara Seas along the Siberian coast; the Barents, Norwegian, and Greenland Seas above the Atlantic; and the Lincoln and Beaufort Seas along the North American coast.

The Arctic Ocean is divided by three submarine ridges into a series of smaller deep oceanic basins. The continental shelf along the Eurasian coast is extremely wide extending out to as much as 700 miles from the coast. The shelf along the North American coast is generally quite narrow and shallow. In the winter almost the entire water surface of the ocean and the seas is ice covered, but the cover retreats somewhat during the summer season. Generally the most open water is found in the Norwegian and Barents Sea area, but narrow open belts occur along the continental coast lines.

The major portion of the arctic area is claimed by the USSR on the basis of their sector principle. The Soviet sector is described as that area up to the North Pole between the meridian 32° 04' 33" E longitude, from Greenwich, running along the eastern side of Vaida Bay through the triangular marker on Cape Kokurski, and the meridian 168° 49' 30" W longitude from Greenwich, bisecting the strait separating the Ratmanor and Krusenstern Islands of the Diomede group in the Bering Sea. This includes the islands and the ice pack on their side of the sector. Svalbard is under Norwegian control, but from an economic and population standpoint is dominated by the USSR. With the exception of Spitsbergen in the Svalbard Archipelago, none of the islands are developed beyond minor hunting and fishing economies. Almost all of the islands have been equipped with weather stations, airfields, and in a few instances radar installations. The only major port directly on arctic waters is the Soviet port of Murmansk, which is ice free throughout the year. The Soviet Northern Fleet is based in this area at several bases on the Kola Peninsula. These sector claims have never been contested by the United States or other nations.

It has only been in recent years that any development of resources along the arctic coasts has occurred. Denmark is developing mineral resources on the northeast coast of Greenland, and the major oil find on the north slope of the Brooks Range in Alaska has sparked a major increase in activity along the entire coastline of Canada and the Canadian Archipelago. Drilling is underway on Banks Island and planned for several of the islands further north. Onshore and offshore leases have been obtained for much of the area to the west of Ellesmere Island. Sketchy reports indicate that the USSR has also caught the arctic oil fever and are in the process of surveying and perhaps even drilling along their northern coast. While such development activity is perhaps only of indirect interest it indicates that there is a growing interest in the arctic and furthermore is likely to indicate an increase in both population and transportation development.

In the past the countries of North America have had little interest in the arctic area except from a curiosity standpoint. On the other hand the development of the arctic seas has been of critical importance to the USSR since the Northern Sea Route represents the main access route to much of the interior of Siberia. This is the prime reason for Soviet political claims in the area.

3.0 DEVELOPMENT OF ENVIRONMENTAL REQUIREMENTS

3.1 DEFINITION OF THE OPERATION AREA

Five elements of the environment should be considered in conjunction with vehicle operation in the arctic. These are shown in Table 3-1.

Table 3-1: ARCTIC OPERATING ENVIRONMENTS

Environment	Operating Mode	Typical Vehicle
Atmosphere	Airborne	Aircraft
Near Surface	Surface Effect	Air-Cushion Vehicle
Surface	Rolling or Sliding	Tracked Vehicle Sled Landing Aircraft
Water Surface	Surface Piercing	Ship Captured-Air Bubble Surfaced Submarine
Water Subsurface	Full Submergence	Submarine

Such classification permits an initial delineation of the gross operating areas and volumes for each type of vehicle.

On this basis the only limitation on the operation of aircraft in the arctic is that imposed by the character of the topography. From the standpoint of an aircraft at high altitude the arctic ice pack is flat, and the only high relief in the terrain is found in some of the coastal areas and the islands. Therefore, an aircraft is free to select both its geographic area of operation and altitude over the ice pack.

An air-cushion vehicle (ACV) must operate at the surface of the ice pack. In this type of operation the topography of the ice pack becomes important; however, in terms of defining the gross operating area ice topography is of secondary importance since it is nonpermanent and can be considered more a hindrance than a barrier. The ACV can be considered as being free to operate at any location on the arctic ice pack.

Vehicles that are confined to the surface must remain on the ice. In the arctic the bearing strength of the ice must be considered a limiting factor and certainly the presence of any open water or rough topography is an effective barrier to movement. The usable area for such vehicles is determined to a large extent by the effects of seasonal variations on the ice pack. The conditions of the ice pack are such that the operation of any surface vehicle other than the smallest and lightest in weight is likely to be confined to extremely limited areas as determined by the boundaries of ice islands and large floes. Therefore, large, heavy surface vehicles for extensive operations can be eliminated from consideration.

Any vehicle, such as a ship or captured-air bubble (CAB) vehicle, that utilizes a wetted hull is obviously confined to areas of open water and to areas where the water depth or ice conditions are such that the vehicle can operate without endangering its safety. Hence the operational area available is automatically defined by the coastal boundries, acceptable water depths, and the boundaries of the ice pack beyond which the vehicle cannot safely penetrate. In the arctic these limitations require that such vehicles remain on the fringes of the ice pack. During the summer penetration to higher latitudes may be possible, but in the winter the operational capabilities become seriously restricted.

A submarine that can remain submerged has an operating area roughly defined by the coastlines and the acceptable differential depth between the bottom of the ice pack and the sea floor. The former is a variable subject to seasonal and climatic changes. Nevertheless the area available for deployment encompasses the major portion of the Arctic Ocean and contiguous seas.

In addition to delineation of the operating areas usable by each type of vehicle, one must also consider system requirements and the impact of the environment on these requirements. Many aspects of any system are closely related to various environmental considerations, and a breakdown is required to aid in the investigation of specific needs. The breakdown utilized in this document is general so that it can serve as a base guideline for any specific end purpose.

The following listing encompasses operational considerations that can be applied to any vehicle or system; however, for each vehicle type additional factors may be necessary to specify operating modes and conditions. System areas that require identification of environmental constraints include:

1) System deployment

   a) Mobility,

   b) Navigation.

2) Reaction

   a) Ability to take station,

   b) Communications.

3) System vulnerability

   a) Detection,

   b) Classification and identification,

   c) Attack.

4) System logistic support

   a) Base access,

   b) Base operation,

   c) Mobile support,

   d) Base vulnerability.

System design considerations are omitted from the list because it is believed that they are largely determined by the requirements indicated in the above categories.

3.2 ENVIRONMENTAL FACTORS AFFECTING MOBILITY AND NAVIGATION

An aircraft in flight is concerned with only two environmental constraints. The flight path must be sufficiently high to avoid any obstacles, and weather that is likely to cause dangerous flying conditions must be avoided. In neither case do these factors prevent an aircraft from flying once it is airborne since current aircraft normally can fly over or around the particular condition or obstacle.

The mobility of the ACV is restricted by the geometry of the surface over which it is operating. This geometry is the surface relief as defined in terms of height differentials and slop gradiants. The effect of the geometry is to impose obstacles over which the vehicle cannot pass or which may seriously impair the effectiveness of the lift fans to maintain an adequate air cushion. Weather

may also affect mobility through reduction of visibility and icing of the skirts and superstructure. Over open water, the surface geometry of the sea (sea state) and the weather factors are highly interrelated.

Waterborne vehicles operating in arctic waters are most likely to be limited by ice conditions as expressed by ice concentration and the movement or stability of the ice pack. Water openings contiguous to the open sea may permit pack penetration and thus improve mobility. Sea state is likely to impose some limitations in the open sea if conditions become sufficiently bad. These effects, like ice stability, are largely dependent on the weather. Visibility conditions and superstructure icing also are related to weather conditions. To a lesser extent, mobility may be limited by water depth.

A submerged submarine is limited in mobility only by the geometry of the bottom of the ice and the water depth. Any mobile system must maintain continuous position plots. The use of inertial systems is well established on submarines and, to a lesser extent, on other types of vehicles; however, since inertial guidance is nothing more than a dead reckoning system, updating is necessary if highly accurate positions are required. Frequency of updating depends on the gyro drift rates and these in turn depend, among other things, on the vehicle stability. For this reason there will always be a need for various land and satellite navigation systems that require the use of radio frequencies. Therefore, all aspects of the environment that are likely to create problems with visual observation and inhibit or interfere with radio frequency propagation are of concern.

Use of radio frequency doppler and altitude systems in aircraft and use of similar acoustic systems on waterborne vehicles also require knowledge of the potential limitations likely in the arctic environment.

3.3 FACTORS AFFECTING AN ABILITY TO REACT

When a system is required to react to an event, there are two prime areas of concern: communications and an ability to take station, if necessary. The need for the former is always likely to be present, while the need for the latter is contingent on the system configuration. The ability to take station can be considered from a somewhat broader point of view and is so considered although it is included in this section.

It is obvious that any vehicle must ultimately come to rest to be replenished or repaired, but it may also be forced to stop for reasons of safety, casualty, or mission accomplishment. With vehicles that do not operate directly on the land, ice, or water surface, this requires that a transition be made from the normal operating environment to the surface. An aircraft must land,

a submarine come to the surface, and an ACV shut down its fans. Environmental conditions at the time and place of this occurrence must permit the vehicle to rest safely. Even vehicles that can operate and stop in a single environment may only do so safely under the right conditions. Once stopped, it is important to consider how long the vehicle can remain at rest safely. Here again the environment must be considered.

Landing an aircraft requires similar conditions wherever the landing is made. If landing aids are neglected, perhaps the most important requirement is adequate visibility; hence, the various factors that encompass surface climatology become important. Of almost equal importance when landing on the pack is the condition of the ice, including such factors as the ice concentration geometry of the surface, and bearing strength of the ice.

The ACV is affected by similar ice features but, with the exception of ice strength, to a lesser extent. If the ACV is equipped with flotation gear, ice concentration becomes less important since the vehicle may come to rest on either the ice or open water. In spite of this possibility, the surface geometry of the ice and the strength of the ice remain important if the vehicle is to assume a stable horizontal position. In large areas of open water in the pack and more especially in the open sea the condition of the sea surface can be of concern.

Stopping a ship or CAB vehicle in or near the edge of the ice is to a large extent contingent on the stability of the ice. If the ice movement and associated weather are such that the vessel may become blocked from further movement and possibly frozen in, it is desirable to keep the vessel underway. Ice concentration in the vicinity of the vessel is, of course, pertinent to this situation. In the open sea a vessel usually must remain underway simply to remain stationary; however, specific conditions of the sea and winds will determine the feasibility of such action.

A submarine, while it is on the surface, faces the same problems as a regular surface vessel. At the same time it has the advantage of being able to rapidly submerge to avoid trouble from the ice pack. The basic problem of the submarine is to find a suitable opening either free of ice, or with ice sufficiently thin to break through. Ice 4 feet or less in thickness has been penetrated by present types of boats. The availability of water openings and the ice concentration therefore becomes a prime concern in underice submarine operations.

System operational or logistic requirements may show a desirability for a vehicle to remain stationary over a period of time ranging from many hours to days. The short- and long-term variability of the environment in regard to each aspect that affects a particular vehicle thus becomes of importance. Weather conditions are perhaps the most critical consideration both because of the effects on the surrounding environment, be it ice or water. A somewhat less obvious concern is the long-term bearing strength of the ice under the load of a vehicle.

Communication problems that are likely to be encountered in the arctic involve two major concerns beyond those encountered in other areas. The first involves the disruption of the ionosphere resulting from auroral activity and magnetic storms, and the second involves the special problem of under ice communication to a submerged submarine.

3.4 SYSTEM VULNERABILITY

The vulnerability of a system depends on an enemy capability to detect, classify and identify, and attack and kill. Since the enemy may chose to use any of the types of vehicles that have been considered, the environmental factors that affect these vehicles must be considered in a determination of system vulnerability. In addition, however, a prime requirement to the enemy is a suitable sensor system to make the initial detection and, if required, classification. The sensors may utilize either the radio frequency spectrum, in the case of airborne or surface targets, or acoustic techniques for a submerged target. Use of infrared, visual, and magnetic techniques are possible, but these are primarily useful for short-range localization. From the standpoint of the environment all factors that serve to block, scatter, attenuate, or otherwise affect the signal-to-noise ratio are of concern. Additionally, environmental features that may appear as false targets are of potential interest. Specific problems that may be encountered by the detection systems are in part determined by the specific equipment and the location in the environment of the vehicle or fixed station using them. Hence, one can recognize only in a very general fashion specific aspects of the environment that may be of concern.

System vulnerability is also affected by the character and defenses of the target. Requirements that may be desirable for radar cross-section or acoustic target strength, for example, are in part dictated by the character of the background. The defensive detection systems may face the same problems as those of the attacker, thus adding an additional set of factors that must be considered.

3.5 SYSTEM LOGISTIC SUPPORT

Many of the environmental constraints that apply to the operational portion of a given system also apply in the areas of logistic support. The location and facility requirements for a given base are definitely related to environmental considerations, as well as the needs of the systems supported. This is especially true in regard to the ingress and egress from support bases for both the deployed vehicles and supply vehicles.

In considering mobile support of a deployed system, the problems that must be faced by the support train are similar to those of the deployed vehicles with the addition of any special environmental problems that occur during a replenishment operation.

3.6 ENVIRONMENTAL FACTORS

Having considered broadly the system aspects that are of concern, it remains to look at the environment in the arctic and to delineate the environment aspects that may be of concern to the system. As is possible with a system, it also is possible to investigate the environment at many different levels. Furthermore, in making such an investigation it rapidly becomes apparent that there are often extremely close relationships between various parts of the environment. For this reason it is extremely difficult in many cases to draw well-defined boundaries within the total environment or within any one aspect of the environment. Nevertheless, practical considerations require that divisions be made.

The environmental factors included in this section and those that follow should be considered in light of these interrelations and the fineness of the divisions taken. It should be expected that much of the finer detail that may be desired for a specific problem will not be found because details are not known at this time. In fact, many of the more gross details of the environment are only poorly known or understood.

The arctic environment for this study can be divided into four broad divisions encompassing:

1) Ice pack characteristics,

2) Climatology,

3) Oceanography,

4) Miscellaneous characteristics.

3.6.1 Ice Pack Characteristics

This division includes all physical and geographic characteristics of the arctic ice pack, including the mechanical properties of the ice and snow. Nine environmental factors are considered. The selection of these nine is based partly on some of the more obvious correlations with the different vehicles and partly on the type of data that is available. These include:

1)	Pack extent	Areal extent of ice coverage,
2)	Ice concentration	Ratio of ice and water present in a given area,
3)	Water openings	Openings in the ice that expose the sea surface,

4)	Ice movement	Motions of the ice pack,
5)	Ice thickness	Thickness between the top and bottom surfaces of the pack,
6)	Surface topography	Relief of the top surface of the ice pack,
7)	Bottom roughness	Relief of the bottom surface of the ice pack,
8)	Ice strength	Mechanical properties of the ice pack,
9)	Cover characteristics	Character and properties of the cover present on top of the ice.

In each case many additional subdivisions are possible, but in the context of the present needs these are unnecessary.

3.6.2 Climatology

The effects of the arctic climate impact all forms of deployment in the arctic in one way or another. Some of these effects are direct, but more often the effect is indirect. Most of the factors included in this division affect visibility in the arctic and also define the overall tenor of the arctic area as it affects human and machine performance. Factors included are:

1)	Temperature	Surface and upper air temperatures,
2)	Cloud cover	Type and extent of clouds,
3)	Surface winds	Winds found predominantly near the surface,
4)	Precipitation	Snow and rain fall,
5)	Surface visibility	Horizontal visibility.

3.6.3 Oceanography

Included in this division are aspects of the Arctic Ocean environment other than the ice pack. These have been reduced to four factors and include:

1)	Bathymetry	Topography of the sea floor,
2)	Sea and swell	Topography of the sea surface,
3)	Tides	Tidal variations in the arctic,
4)	Sound propagation	Environmental effects on the propagation of sound in the water.

Many aspects of the environment have been omitted in this division. These omissions have been rationalized on the basis that they have no direct impact on system operation. For example, temperature, salinity, and biological aspects of the environment are considered to be primarily of concern in regard to sound propagation and of little direct impact in other ways. This is an obvious simplification.

3.6.4 Miscellaneous

This division is included to accommodate environmental factors that do not fall directly in the above divisions as well as those that depend in part on the operating characteristics of system components. Included are:

1)	RF propagation	All aspects of the environment that may affect the propagation of radio frequencies,
2)	Radar clutter	All aspects of the environment that affect the scattering of radar frequencies,
3)	Albedo	Reflectivity of the ice and water surface at visual optical frequencies,
4)	Sunlight/moonlight duration	Duration of time which the sun or moon is above the horizon.

The last two have an important impact on visibility, particularly over the ice pack. The first two, while obviously important, are not covered in this report.

3.7 VEHICLE MATRICES

With a definition of system operating conditions and major environmental considerations, it is possible to combine these in the form of matrices to indicate specific points of impact by

different aspects of the environment. Four matrices are included, Figures 3-1 through 3-4, showing these relationships for aircraft, air-cushion vehicles, ships and captured-air bubble vehicles, and submarines. At each point of interest, reference is made to the appropriate section in the environmental portion of this report when the information is included.

Logistics has been omitted, not because it is unimportant, but rather due to complexity and extension of the required geographic boundries beyond the area covered in this report. In addition, no attempt is made in the matrices or elsewhere to consider specifically how a particular environmental factor impacts a particular vehicle or system.

AIRCRAFT			ICE PACK									OCEANOGRAPHY				CLIMATOLOGY					MISCELLANEOUS				
			PACK EXTENT	ICE MOVEMENT	ICE CONCENTRATION	WATER OPENINGS	ICE THICKNESS	SURFACE TOPOGRAPHY	BOTTOM TOPOGRAPHY	ICE STRENGTH	COVER CHARACTERISTIC	BATHYMETRY	SEA AND SWELL	TIDES	SOUND PROPAGATION	TEMPERATURE	SURFACE WINDS	PRECIPITATION	CLOUD COVER	SURFACE VISIBILITY	RF PROPAGATION	RADAR CLUTTER	ALBEDO	SUNLIGHT/MOONLIGHT DURATION	
DEPLOYMENT	MOBILITY																								
	NAVIGATION																		●		●	●		●	
REACTION	ABILITY TO TAKE STATION	AIRBORNE																							
		ON SURFACE	●		●		●	●		●	●						●			●					
	COMMUNICATIONS																				●				
VULNERABILITY	DETECTION	AIRBORNE																			●	●			
		ON SURFACE						●										●	●	●	●	●	●	●	
	CLASSIFICATION/ IDENTIFICATION	AIRBORNE																	●					●	
		ON SURFACE																●	●	●			●	●	
	ATTACK	AIRBORNE																			●	●			
		ON SURFACE																		●	●	●	●	●	

Figure 3-1

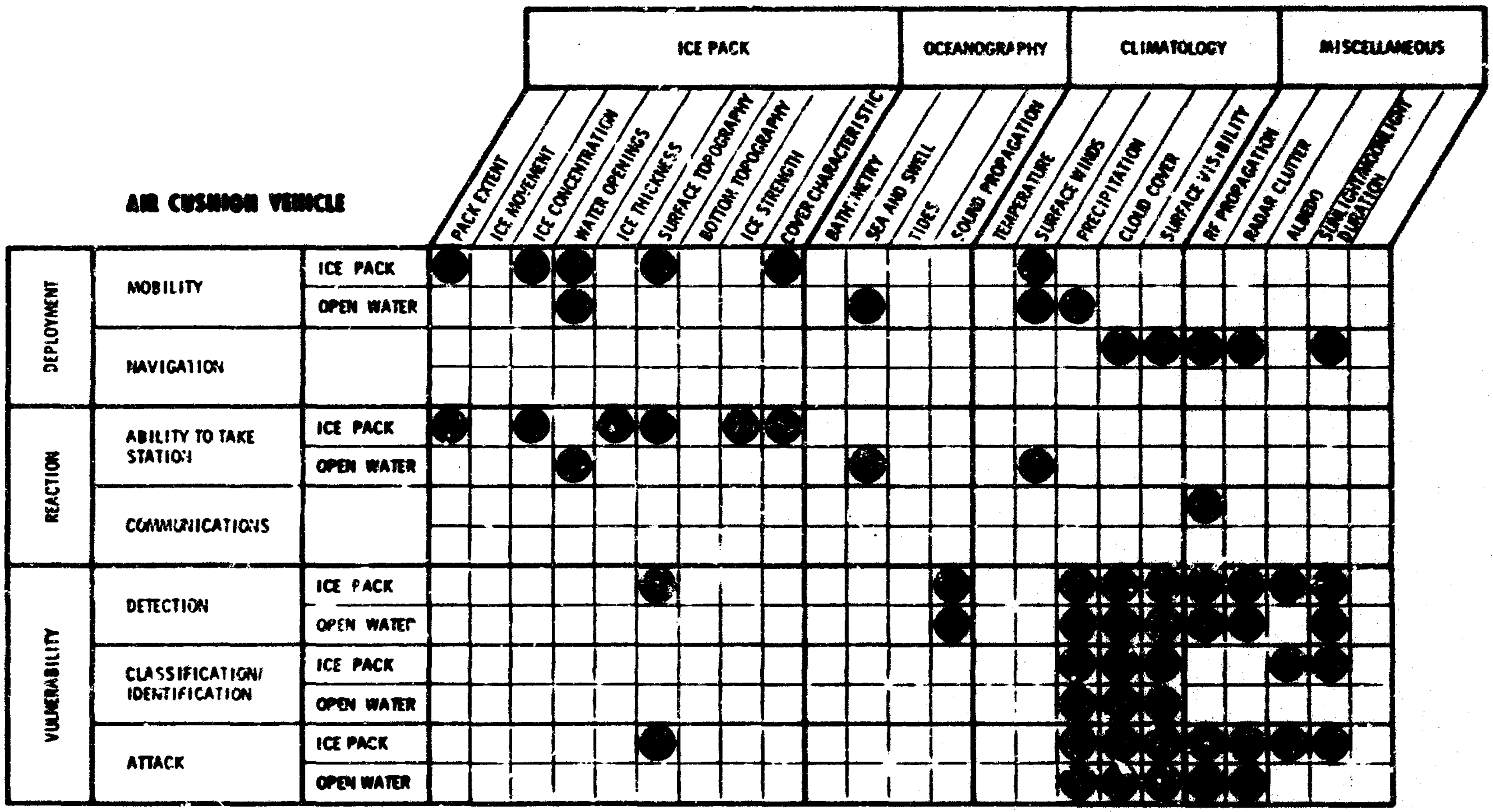

AIR CUSHION VEHICLE
ICE PACK
OCEANOGRAPHY
CLIMATOLOGY
MISCELLANEOUS
PACK EXTENT
ICE MOVEMENT
ICE CONCENTRATION
WATER OPENINGS
ICE THICKNESS
SURFACE TOPOGRAPHY
BOTTOM TOPOGRAPHY
ICE STRENGTH
COVER CHARACTERISTIC
BATHYMETRY
SEA AND SWELL
TIDES
SOUND PROPAGATION
TEMPERATURE
SURFACE WINDS
PRECIPITATION
CLOUD COVER
SURFACE VISIBILITY
RF PROPAGATION
RADAR CLUTTER
ALBEDO
SUNLIGHT/MOONLIGHT DURATION
DEPLOYMENT
MOBILITY
NAVIGATION
REACTION
ABILITY TO TAKE STATION
COMMUNICATIONS
VULNERABILITY
DETECTION
CLASSIFICATION/ IDENTIFICATION
ATTACK
ICE PACK
OPEN WATER

Figure 3-2

SHIP/CAPTURED AIR BUBBLE

			ICE PACK									OCEANOGRAPHY				CLIMATOLOGY					MISCELLANEOUS				
			PACK EXTENT	ICE MOVEMENT	ICE CONCENTRATION	WATER OPENINGS	ICE THICKNESS	SURFACE TOPOGRAPHY	BOTTOM TOPOGRAPHY	ICE STRENGTH	COVER CHARACTERISTIC	BATHYMETRY	SEA AND SWELL	TIDES	SOUND PROPAGATION	TEMPERATURE	SURFACE WINDS	PRECIPITATION	CLOUD COVER	SURFACE VISIBILITY	RF PROPAGATION	RADAR CLUTTER	ALBEDO	SUNLIGHT/MOONLIGHT DURATION	
DEPLOYMENT	MOBILITY		●	●	●		●			●		●	●	●			●			●					
	NAVIGATION																		●	●	●	●		●	
REACTION	ABILITY TO TAKE STATION		●	●	●								●				●								
	COMMUNICATIONS																				●				
VULNERABILITY	DETECTION																	●	●	●	●	●	●	●	
	CLASSIFICATION/ IDENTIFICATION																			●	●	●		●	
	ATTACK																	●	●	●	●	●		●	

Figure 3-3

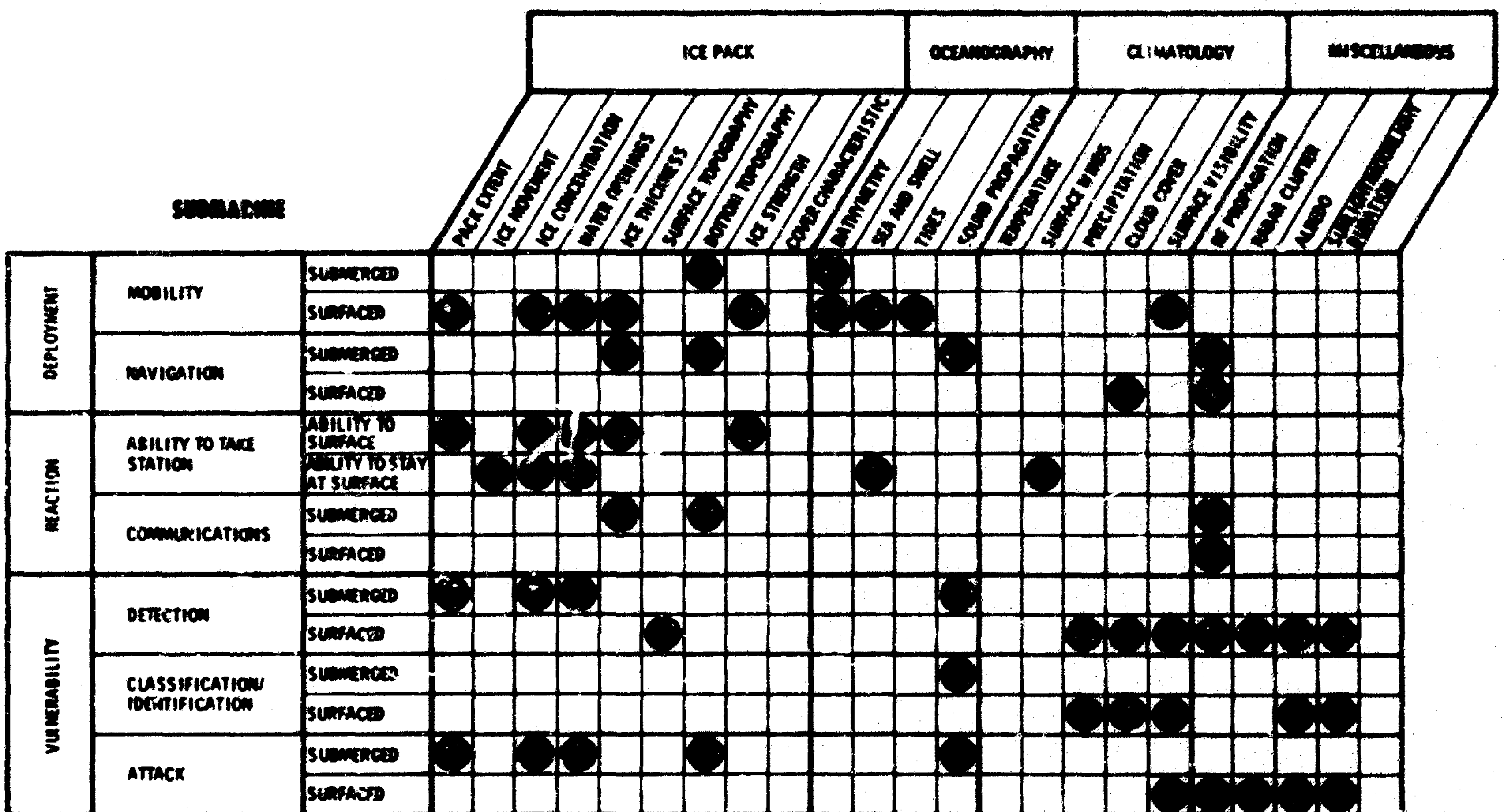

ICE PACK
OCEANOGRAPHY
CLIMATOLOGY
MISCELLANEOUS
PACK EXTENT
ICE MOVEMENT
ICE CONCENTRATION
WATER OPENINGS
ICE THICKNESS
SURFACE TOPOGRAPHY
BOTTOM TOPOGRAPHY
ICE STRENGTH
COVER CHARACTERISTIC
BATHYMETRY
SEA AND SWELL
TIDES
SOUND PROPAGATION
TEMPERATURE
SURFACE WINDS
PRECIPITATION
CLOUD COVER
SURFACE VISIBILITY
RF PROPAGATION
RADAR CLUTTER
ALBEDO
SUBMARINE
DEPLOYMENT
MOBILITY
SUBMERGED
SURFACED
NAVIGATION
SUBMERGED
SURFACED
REACTION
ABILITY TO TAKE STATION
ABILITY TO SURFACE
ABILITY TO STAY AT SURFACE
COMMUNICATIONS
SUBMERGED
SURFACED
VULNERABILITY
DETECTION
SUBMERGED
SURFACED
CLASSIFICATION/ IDENTIFICATION
SUBMERGED
SURFACED
ATTACK
SUBMERGED
SURFACED

Figure 3-4

4.0 ENVIRONMENTAL KNOWLEDGE

4.1 BACKGROUND

The material utilized in this study has been derived from both documented and undocumented sources. The report contents therefore represent a compliation of data that indicates both the salient characteristics of the arctic and the present state of available knowledge in the areas covered.

There is no single complete or even partial compilation of environmental data covering the arctic. Available data is highly fragmented in that no one communications medium directed toward the arctic is utilized by researchers. For this reason, the sheer magnitude of the work in surveying the literature is monumental, and in the present report no claim is made that all sources have been consulted. Particularly lacking is information from Soviet sources. Soviet activity in the arctic has been far more extensive than that of any other nation in terms of time, manpower, and types of activity. Yet the vast majority of this information does not seem to be available in the United States or Canada. It is possible, of course, that much of this information has never been transmitted outside the Soviet Union.

4.2 STATE OF KNOWLEDGE

Knowledge of the arctic environment and even of the arctic in general can best be described as minimal. This is not surprising, however, in view of a lack of national interest in the arctic. Perhaps it should be considered surprising that there are enough dedicated individuals working to obtain the information that is available. It is most informative to an understanding of the overall situtation to review the report on Federal arctic research prepared by the Library of Congress for the Senate Appropriations Committee in early 1968 (Reference 1).

The funding at that time amounted to about $40,000,000 divided among 23 agencies, but the bulk of this sum went to DOT, DOD, and the Interior Department. The major portion of the DOT sum went to the Coast Guard for arctic ice breaker operation. Almost all of the work performed in the Interior Department was done in Alaska and along the Pacific and Bering Sea coasts and represented research on natural resources and fisheries. About half of the DOD funds went to the Army for work at their arctic and cold weather laboratories as well as the Alaskan test ranges. Navy funding amounted to about $2,000,000, which was widely disbursed in the form of small ONR grants and presumably to operate the laboratory at Barrow. Air Force funding was divided between seismic and arctic-survival research. In addition to the sums indicated here

there were obviously some classified projects. A key point not obviously apparent is that the amount of funding spent for work on or related to the arctic ice pack was probably less than $300,000, if all conceivable leeway is taken in making this determination.

The general disinterest in the arctic is also indicated by the lack of coordination and cooperation between the agencies. Cooperation at the field and personal level is evident through exchange use of facilities and research results, but little such cooperation exists at higher levels.

The problem of obtaining data, particularly when one is concerned with an area such as the ice pack that has had little research effort, is at best difficult. More often than not areas of particular concern have never been investigated; or, if they have, only minor amounts of work have been expended. Some areas such as climatology are significantly better than others because there has been a requirement for such information. Submarine operations have created both a need and a capability for obtaining bathymetric data and data on sound propagation under the ice pack itself. Up to now, however, there has been little or no need for data on the upper surface of the pack.

Accordingly, the data contained in the environmental sections of this report represents the best obtainable information. It is fairly certain that there is some additional data that would add to the utility of these sections and perhaps even partially fill gaps, but in many cases this data is still in the raw form as taken in the field because of a lack of time, manpower, and money to accomplish the processing task. In many cases access is blocked because of classification. It is felt, however, that even the addition of this data would make little improvement in the overall picture, particularly in regard to specific problems.

It is apparent that if future military considerations might involve operations on or under the ice pack covering the Arctic Ocean that even a limited program of well-planned and conducted research directed toward specific operational problems is essential.

4.3 REFERENCES

1) Doumani, G. A. (1968), Federal Arctic Research, Senate Document No. 71, 90th Congress, 2nd Session.

5.0 MECHANICAL PROPERTIES OF ICE AND SNOW IN THE POLAR BASIN

5.1 INTRODUCTION

In the Arctic Ocean, there is diversity in the physical and chemical properties of its waters. The basin receives fresh water from some of the rivers rated among the major ten resulting in a large influx of fresh water that reduces the usual ocean salinity. In addition, these rivers carry large quantities of solute and particulate material from the adjacent land margins, which creates significant turbidity currents in the adjacent seas.

The geographic core of this basin is ice and snow covered. Such a covering would offer no problem towards understanding the physical properties of the ice if it were not in constant dynamic motion. It is necessary to recognize the existance of these dynamics to understand the mechanical properties of the arctic ice pack.

Most ice and snow studies to date have been cursory, having been taken during short time intervals or restricted to locations near land and spots on the ice islands. Furthermore, these studies have not been directed toward engineering uses or systems that must operate in the polar ocean environment. This is not to imply that there is no useful data. Some of the early explorers, such as Nansen and Sverdrup, were able scientists and some of their data is still used. The Soviet scientists were among the first to recognize the need for obtaining better data, but the data is difficult to obtain and much of the instrumentation was apparently of poor calibre.

5.2 SEA ICE

5.2.1 Components of Arctic Sea Ice

The water in the Arctic Ocean like all ocean water is a solution of complex salts, and it is from this solution that the arctic sea ice forms. The water of the polar basin contains three basic inclusions: (1) organic molecules, (2) particulate matter, and (3) inorganic molecules. These inclusions are important because they determine the ultimate strengths of the sea ice, which is sensitive to both the impurity concentrations and freezing parameters.

Organic materials present in the arctic waters come from a diversity of sources of sea life, as well as materials carried into the basin by the rivers. These original biota and their wastes are in greatest concentration at places where there are currents of considerable temperature variation, or they occur during seasons when there is peak flow in the river basins. To date

there has been no research work on the importance of such organic inclusion in ice as a function of the mechanical properties.

The rock or skeletal material is most significant near the shores of the polar basin where the waters are relatively shallow and turbulance can suspend appreciable amounts of matter in the waters. The materials are derived from the sedimentary flatlands surrounding the Arctic Ocean. As such, the materials are generally 50 to 80% fine silts, sands, or nonplastic clays, with the majority of the remainder being medium to soarse sands, and a lesser percentage of cobbles or larger rocks. Among the fringes of the permanent pack, surface wind transport brings fine rock and soil to the snow and ice surface. Such rock material strengthens the physical character of cold ice, but it also increases surface melting of spring ice.

Salt concentration is an important factor in the mechanical properties of sea ice and, although the concentration of ionized salts varies between ocean zones, the composition is generally uniform.

5.2.2 Natural Ice Material

The range of structure in different kinds of ice is basically one of degree. However, since salt ice has a very high percentage of included matter, fresh-water ice can be considered almost pure by comparison. The most basic difference is where the inclusions are located. In salt ice small polygonal ice segments make up the total ice structure, and the salt inclusions lie between the polygons; in fresh-water ice the salts are mainly at the grain boundaries. This is the major reason why salt ice seems to hold its structural qualities until it is almost all melted. The melting is analogous to slowly enlarging the holes in swiss cheese, in which case the solid holds its structural character until the voids occupy the majority of the volume.

The ice of interest in the arctic is a polycrystalline material (containing all the inclusions suggested in Section 5.2.1. This ice is a visco-elastic solid. It will follow Hooke's law as an elastic material to a point, after which a constantly increasing shear strain results from the application of a shear stress. It should be noted that the rate of stress application is very important. For sea ice rapid application of stress over a short time period yields a large elastic range, but as soon as the elastic limit is reached failure occurs because the ice has a very small plastic range. Slow application of load also leads to interesting results.

Sea ice is under a state of constant phase change due to salt liquid inclusions. Thus, the latent heat of fushion is a variable, with a continuous phase change from fluid to solid with decrease in ambient ice temperature. The specific heat of the sea ice is quite sensitive if the salinity

concentration is high and the ice is near its freezing point. As it recedes from this temperature and high salinity, the specific heat becomes smaller and more stable.

5.2.3 Freezing Process of Arctic Sea Water

The first consideration of sea ice is the freezing process because it gives insight into mechanical properties. However, after the ice covering forms on the water surface, the salinity of the adjacent water becomes the important parameter. The sea is an infinite heat reservoir and, by its innate thermal properties, releases heat which in turn governs the temperature at the ice/water interface. (References 1, 2, 3, and 17)

The freezing of any aqueous ice is a unique phenomena. Water is one of the few materials that expands upon solidification, during which process the crystal lattice reacts in a very selective way. Thus, no substitution can take place for hydrogen or oxygen atoms. From a mechanical property aspect this means that, if the solution is frozen slowly, any foreign ions present will remain as free agents in the crystal matrix. Therefore, the structural components of the ice are relatively pure and salts remain as interlattice solutes.

In nature, the freezing process is generally so rapid that a certain amount of the "impurities" remain as free agents in the lattice. If an average figure is chosen for the entire basin, the figure for salinity is 5 to 8 parts/thousand. This means that for practical purposes between 80 and 90% of the salt is excluded during the freezing process.

Since this solution is a eutectic mixture, a point is reached at about -21°C below which the brine will not exist. For practical considerations this low temperature region is not as important as the temperature region between zero and -5°C. (References 2, 4, 14, 16, 17, and 24)

5.2.4 General Polar Ice Types

The freezing process lowers the ambient temperature to the freezing point and then continues to remove heat from the surface waters. The coagulation and solidification begins with the formation of small ice polygonal forms (frazil). After sufficient ice coagulants have floated to the sea surface a primordial ice cover forms, which is a very flexible coating. It is usually described by observers as the "oily surface." As the small polygons occur they form into regular anisotiopic layers, which are parallel to each other and with their c/axes perpendicular to the polygonal layers. It also appears that near-surface crystals are small and increase in the horizontal dimension with depth from the surface. Small-size crystal inclusions

are visible throughout the depth of a sea ice sheet. Although the system is in an unstable state due to temperature, and time is required for a mix of any given area concentration, certain size relationships exist. Table 5-1 describes types of ice. (References 1, 5, 21, and 33)

Table 5-1: ICE TYPES

Ice: Sea Water Crystal	Primordial polygons of young or seasonal winter ice	0.5 to 0.6+ mm
Size Relationships	Fluid salt pocket	0.04 to 0.075 mm
Size (average thickness)	Mature seasonal ice	1 to 5 cm + dia., and 0.5 to 1.5 ± meter vertical size (source variance).
References 4, 15, 27, 46, and 20		

5.2.5 Movement of Salt Ions

The salts in the ice sheet are in constant movement within the crystal lattice. Some of the salts remain temporarily in certain portions of the normal crystal patterns as progenitors of various kinds of faults in the crystal makeup. The remainder of the salt concentrations are in a steady motion state through the ice sheet. First, this portion of the salt solution is located as layers between the ice crystals. Next, ice forms across the layers, forming cells filled with salt solution. As time passes the cells interconnect and form tubes. As these tubes grow they either tend to migrate toward areas with warmer temperatures, or they form ducts from which brine then drains back into the sea waters. It is by thermodynamic solution, drainage, and diffusion that fresh-water ice forms on a salty sea. (References 17, 18, 27, 29, 32, 45, and 54)

5.2.6 Arctic Polar Sea Ice Types

As noted above, the dynamically unstable sea ice is undergoing constant change of form. Thus, it is easy to understand how the mechanical properties of sea ice can vary due to the concentration changes of salts, as well as the parameters of temperature and pressure. Under these forcing functions the ice is in a metamorphic process. (References 1, 12, 21, 30, 32, 38, 46, 51, 55, and 56)

It is not practical at this time to differentiate a great number of ice types, but if a generalization is made for the purpose of clarification, three ice types appear as basin occupants: annual ice , biannual ice , and land ice which have broken loose and are floating about. All types are controlled by the dynamics of the basin.

Annual ice is made up of material one season or less in age. This ice can be either very young or of an age dating from midwinter to the end of the season. Such ice is noted on the edges of continents, in island channels, in open waters in semipermanent ice such as polynyas, and in the natural current areas south of the polar pack. Its dynamics are such that the prime strength parameters are cuased by mode of formation and temperature or pressure components during its life span.

Biannual ice or semipermanent ice is generally called polar ice. These are ice forms that cover the polar basin waters for more than one season and are ices termed by explorers as permanent polar pack. Such year-around ices have a characteristic blue color. The ice probably grew in thickness from 2 to 4 meters the first season, after forming in open water. Then in the warm spring, summer, and early fall the ice rejects salt to the sea. When the surface melts, fresh water forms in pools. By this method of thawing on the surface in summer and freezing from below in winter, the ice grows and becomes stronger. Thus, layers of this ice move gradually from the lower surface to the upper surface of the pack. In old age such ice can become 4 to 5 meters thick.

Another form of ice present in the basin is glacier ice, which appears as bergs, old glacier ice that has flowed into fjords or into piedmont coasts next to valley glaciers, and grounded ice found as a foot against the land on shallow coasts. This latter form is usually found only on the fringes of the basin.

5.2.7 Specific Polar Ice Classes

In order to form a useful classification of mechanical properties, five ice types are defined (Table 5-2). Two are seasonal, two are semipermanent, and one is a dislocated land form.

Table 5-2: ICE CLASSIFICATION FOR MECHANICAL PROPERTIES

Type	Name	Characteristics
1	Young ice	Ice formed in a period of hours to several weeks
2	Winter ice	Ice formed during one winter
3	Biannual ice	Ice formed over a period of one winter and less than two winters
4	Polar ice	Ice formed in the perannual pack zone in a period of more than one winter season
5	Land ice	Ice formed as shelf, berg, or "ice island" material. This is ice that forms on land and subsequently either floats as land-attached ice, as islands (i.e., T-3), or as some form of berg.

Young ice is a relatively weak material that has significant layers of included salt solution, and its original geometry varies from complex to regular. If it is less than several weeks into the metamorphic process, it has not yet developed great bending strength but does have considerable elasticity. It is gray in color, has considerable permeability, and is less than 1 meter in thickness. This is a weak ice in most mechanical properties.

Winter ice is young ice which increases in thickness as the winter progresses. It is gray to gray-white in color and is similar to young ice in its permeability. This ice is much more anisotropic than young ice and has extruded much of the salt layers to include the salt in tubes and cells. This material has much greater strength in bending and other mechanical properties. Its upper surface has an aging snow cover with its added specific strength characteristics.

Biannual ice has a thickness of at least 2.5 to 3 meters. It has turned blue to blue gray in color. The ice has extruded salt solutes during a warm season; contains considerable fresh-water ice, fresh-water ponds, or slush; and sometimes has included rock or fine particulate matter. It is relatively strong, but more brittle than young or winter ice. It also has faulting and major structural discontinuities, and is a truly crystalline solid.

Polar ice is 4 to 5 meters in average thickness. It is more than two seasons in age, and has undergone considerable exclusion and regeneration of salt into the pack. The material is only relatively less permeable than other forms. The color is blue, steel blue, or grey blue, depending on the metamorphic stage, and the strength is determined by the specific temperature and pressure environment. It is a crystalline solid.

Land ice includes all forms, but is best known as ice island or berg ice. It is the strongest type found in the basin since it is formed under pressure influences. This material is generally not very permeable and is strongly anisotropic. It clearly relfects its plastic flow genesis.

There is considerable variety in specific form of crystal structure and interbedded or included particulate matter. Due to metamorphic aging, land ice is the most stable type against temperature and pressure melting.

5.2.8 Location of Arctic Polar Ice Types

In general, the stronger ices appear in the center of the basin because there is time for the ice to age and remove some of its salt content. The other major sector of strong ice is near islands in "cold belts" and where bergs and ice islands drift into the basin. The weaker ice types are between the permanent ice pack and the surrounding land masses. Weaker ices also exist where major currents meet or upwellings bring significant increases in salt concentration in the ocean waters. Table 5-3 lists major ice locations and types. (References 4, 6, 12, 13, 21, 30, 31, 38, 40, 46, 48, 51, 55, and 56).

Table 5-3: FORECAST OCCURRENCE OF ICE TYPES

Location	Season			Remarks
	Fall	Winter	Spring	
Barents Sea	1	1,2,3	1,2,3	3 in interior, 5 possible
Kara Sea	1	1,2,3	1,2,3	3 in interior, 5 possible
Laptev Sea	1	1,2,3	1,2,3	May have 4
East Siberian Sea	1	1,2,3	1,2,3	May have 4, 3 in interior, 5 possible
Chukchi Sea	1	1,2,3	1,2,3	May have 4, 3 in interior, 5 possible
Beaufort Sea	1	1,2,3	1,2,3	May have 4, 3 in interior, 5 possible
North of Canadian Arctic Islands	1,3,4	1,2,3,4	1,2,3,4	Very pressure sensitive, 5 possible
Interior Canadian Portion Arctic Basin	1,3,4	2,3,4	2,3,4	5 possible
Eurasian Portion Arctic Basin	1,3,4	1,2,3	1,2,3,4	

NOTE: 1 = Young Ice; 2 = Winter Ice; 3 = Biannual Ice; 4 = Polar Ice; 5 = Land Ice

5.2.9 Major Physical and Mechanical Properties

5.2.9.1 Density

There is considerable variation in density-determination values for various forms of polar pack ice. This could be caused by either the geographic location of the samples or the measurement techniques. It is generally agreed that for either annual Type 1 or polar Types 3 or 4 the densities are quite uniform for a given geographic ice sector. First measured approximation values for the ice types defined are given in Table 5-4.

Table 5-4: DENSITY, g/cm^3

Ice Types	Fall Season	Winter Season
Young	0.85	0.88
Winter	0.88	0.91
Biannual	0.91	0.92
Polar	0.92	0.94
Land	0.94	0.96

NOTE: No variation is shown because the values are approximations. The temperature regime is assumed to be -5 to -20°C.

It should be noted that the densities listed are explicitly for use by mechanical or civil engineers or designers. These values are not intended for use in sound propagation or electrical work on the sea ice. (References 3, 5, 13, 20, 37, and 49)

5.2.9.2 Poisson's Ration/Young's Modulus

It can be seen from Figure 5-1 that the brine content is quite significant in relation to Young's Modulus (E). To obtain a representative Young's Modulus, it is assumed that the ice temperature is low enough to give fairly reproducible values. When the temperature approaches 0°C the salt content and air content in the included void spaces give erratic results.

Figure 5-2 shows the values of E for the four types of polar sea ice. Some researchers believe that the brine content is a linear function of E, but since there is doubt about some of this work, the values are shown in an integrated strip. The plot also shows a region of values for the beginning of the cold weather season and a region for the coldest temperature period. (References 9, 13, 15, 20, 26, 27, 42, and 51)

5.2.9.3 Unconfined Compression Strength

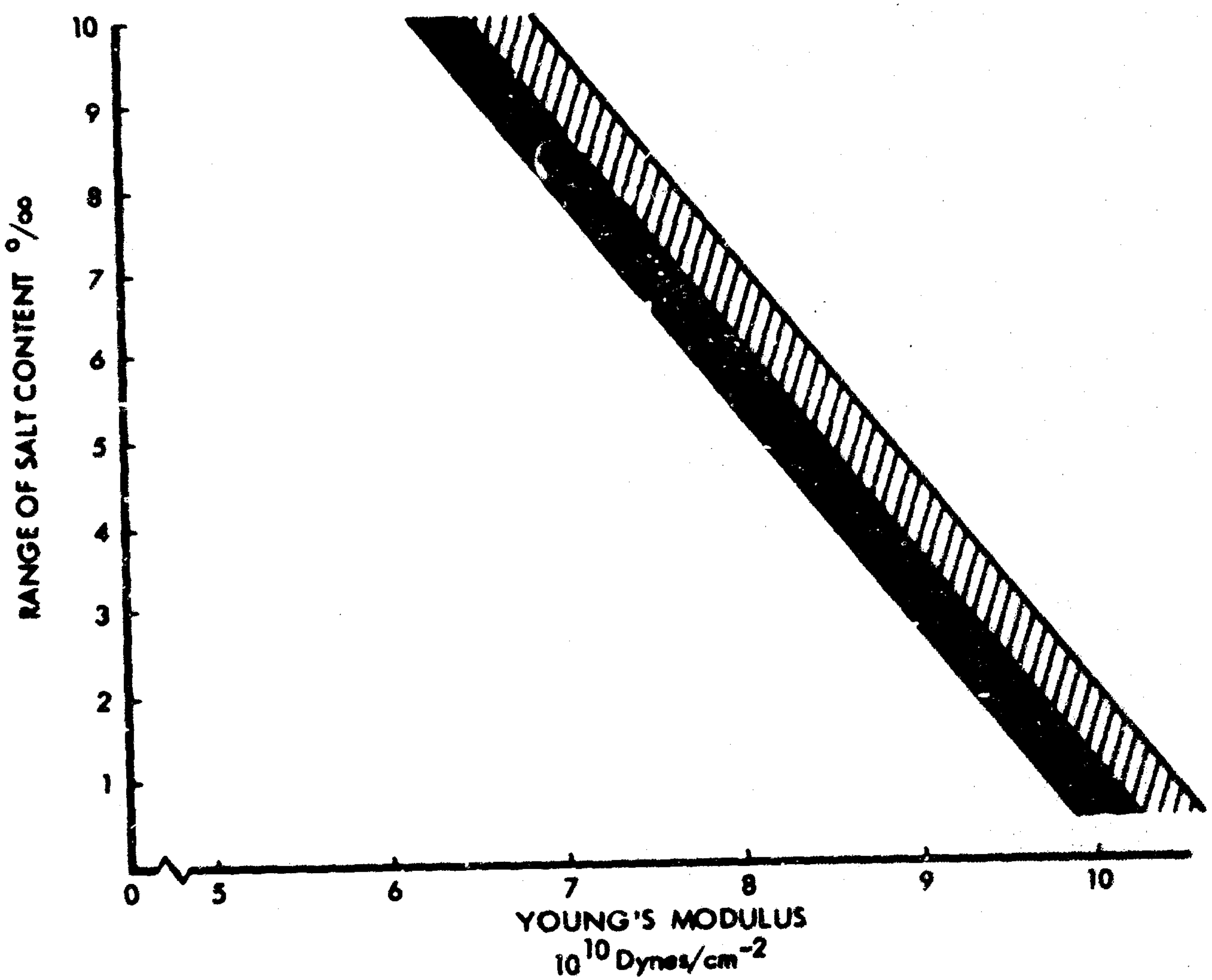
The unconfined compressive strength of sea ice is one of its most important mechanical properties. For all types of arctic sea compressional strength increases with a decrease in either the salt content or temperature. The compressional strength also increases with metamorphic aging. Most of the tests performed on sea ice have been conducted with the stress parallel to the direction in which the ice freezes.

Figure 5-3 shows the unconfined compression expected for the four types of sea ice. The curves consider the increase in strength which occurs with a decrease in temperature. If the ice is near the zero freezing point, the values should be degraded as follows: Type 1 by 20%; Type 2 by 14%; Types 3 and 4 by 10%. For temperatures between -10 and -20°C average values can be taken from the curves. For very cold values such as -40°C the values can be increased approximately 15%. (References 5. 7, 10, 14, 17, 22, 38, 41, 47, and 51)

5.2.9.4 Tensile Strength

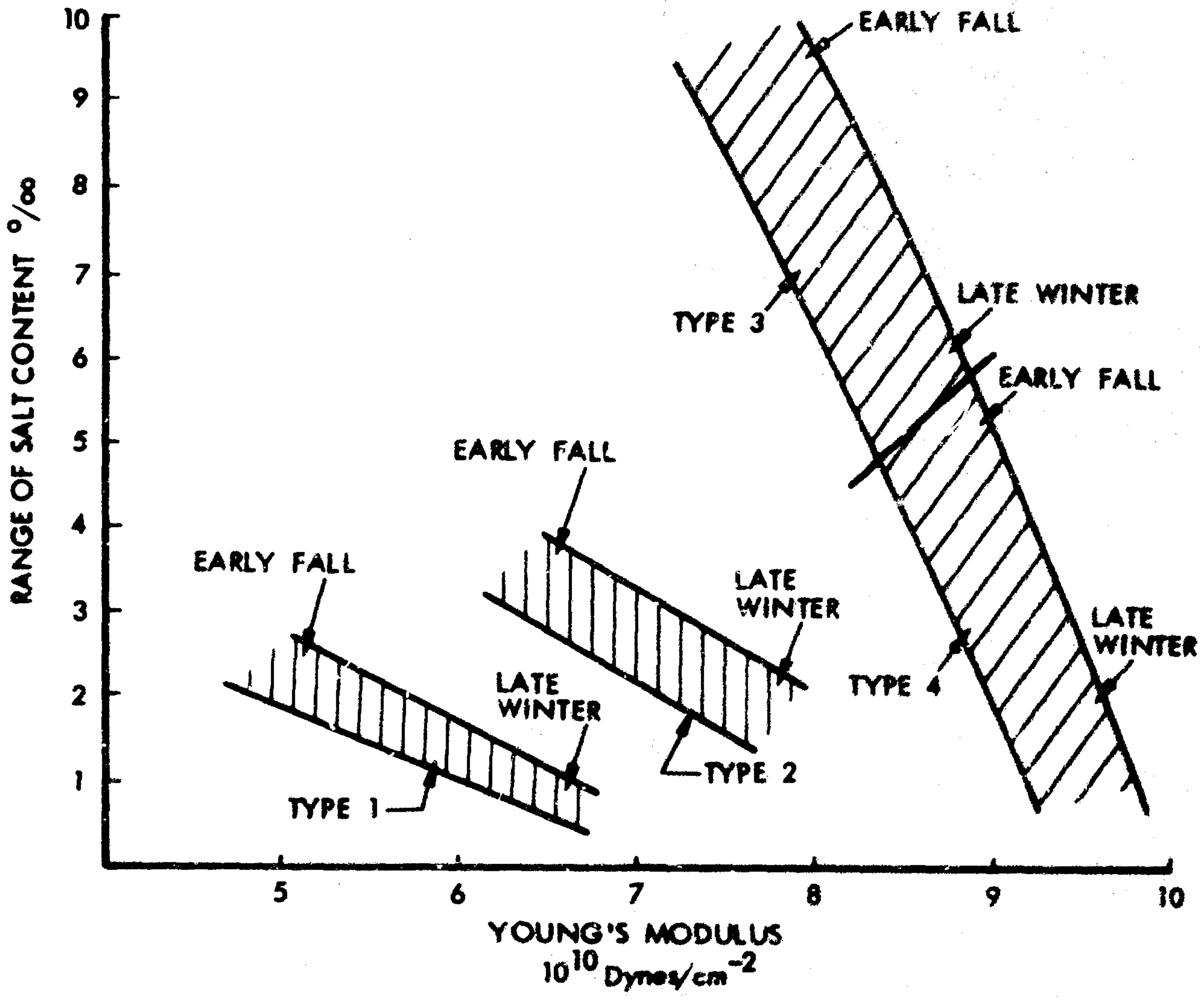
The next most important mechanical property of the sea ice is its tensile strength. Results obtained in determination of the tension characteristics of polar ices in fall or summer have shown the importance of the salt content in strength values.

Figure 5-4 shows the values to be expected for the four major ice types. The strength of the ice increases with a decrease in temperature and a decrease in salinity. If the tensile strength of the ice is to be taken near the freezing point, all values should be degraded 10 to 15% with Ice Types 1 and 2 receiving the higher factor. (References 2, 5, 9, 10, 14, 15, 21, 22, 23, 41, 47, and 53)



AFTER BUTKOVICH, LANGLEBEN, POUNDER AND OTHERS

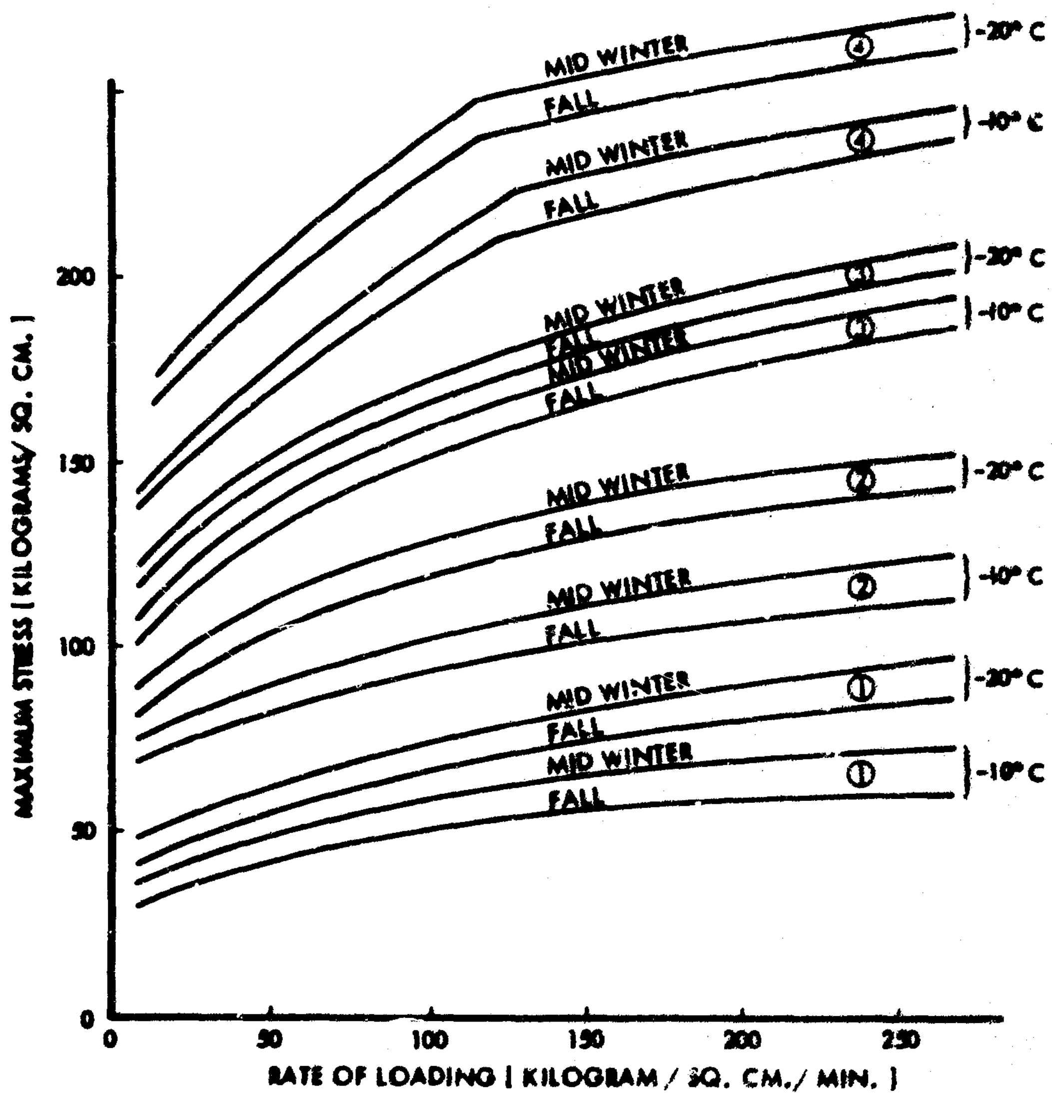
Figure 5-1: YOUNG'S MODULUS---COLD POLAR ARCTIC ICE



NOTE. ICE TYPE 1 = YOUNG 3 = BIANNUAL ICE
2 = WINTER 4 = POLAR ICE

TYPES 1 AND 2 ARE QUITE SENSITIVE TO SALT INCLUSION CONTENTS. TYPES 3 AND 4 HAVE EVEN HIGHER YOUNG'S MODULUS. ALL TYPES SHOWN ARE FOR ICE LESS THAN -5°C.

Figure 5-2: YOUNG'S MODULUS---EXPECTED ICE TYPES



NOTE: ICE TYPE 1 = YOUNG 3 = BIANNUAL
2 = WINTER 4 = POLAR PACK

AFTER BUTKOVICH, LANGELEBEN, BARNES, POUNDER, GLEN, AND OTHERS

Figure 5-3: COMPRESSIVE STRENGTH FOR MAJOR ARCTIC SEA ICE TYPES

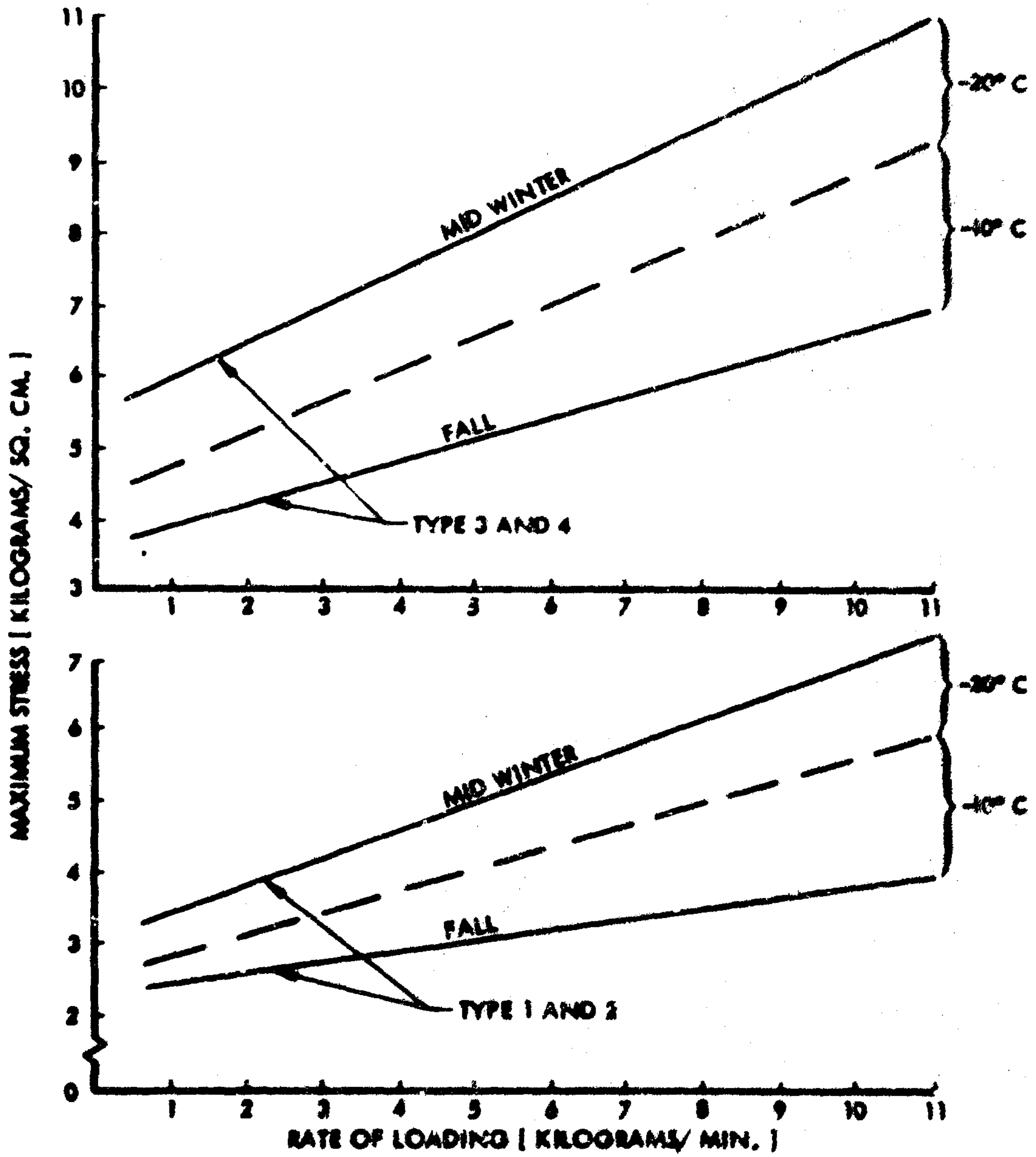


Figure 5-4: TENSILE STRENGTH FOR MAJOR ARCTIC SEA ICE TYPES

5.2.9.5 Shear Strength

The shear strength of sea ice can be a very important property for some type of systems operating in the polar basin, but unfortunately it is difficult to measure the shear stress. Tests to date have been made on cylinders which were carefully fitted to each other then slid over a core (4-inch cylinder over a 3-inch core). The cylinders on the ends were held fixed while a transverse force was applied to the middle cylinder until the ice failed in shear at both ends. The shear was applied transverse to the length of the columnar ice crystals. The ice cores were taken vertically in the pack.

Figure 5-5 shows the expected values for the four major ice types in the basin. The values of shear increase with a decrease in temperature and salinity. (References 3, 10, 14, 23, 27, 29, 31, 36, 41, 47, and 51)

5.2.9.6 Ring Tensile Strength

The importance of ring tensile strength is in understanding the load-bearing nature of the polar ice. If the floating ice is loaded by an amount greater than the bearing capacity of the ice, it will fail under shear. The sea ice can vary in basic type and in salinity and temperature. After the ice has reached about 15 cm, it begins to take on reasonable ring tensile strengths. For young sea ice, the values are low because it is both thin and high in salt content. Such ice begins to achieve the strengths of early winter ice if initial growth permits a significant thickening and the metamorphic process is in force long enough to create some orderliness in the crystal lattice.

Work on this property shows that the most reproducible and understandable results have been obtained in the field on insitu samples. In practice Assur, Butkovich, and others have taken 3-inch cores (vertical) and drilled concentric cores through the sample (1/2-inch diameter holes along the axis). The samples were then loaded normal to the axis of the sample. Testing bears out theory, which states that the maximum stress concentration occurs around the drilled hole. The empirical equation for the ring tensile strength is:

$$\text{R.T.S.} = 29.0 - 53\,(\text{fraction volume of salt content})^{1/2}$$

For a more practical usage, the ring tensile strength can be considered to decrease linearly by the square root of the salt content fractional volume $^{1/2}$.

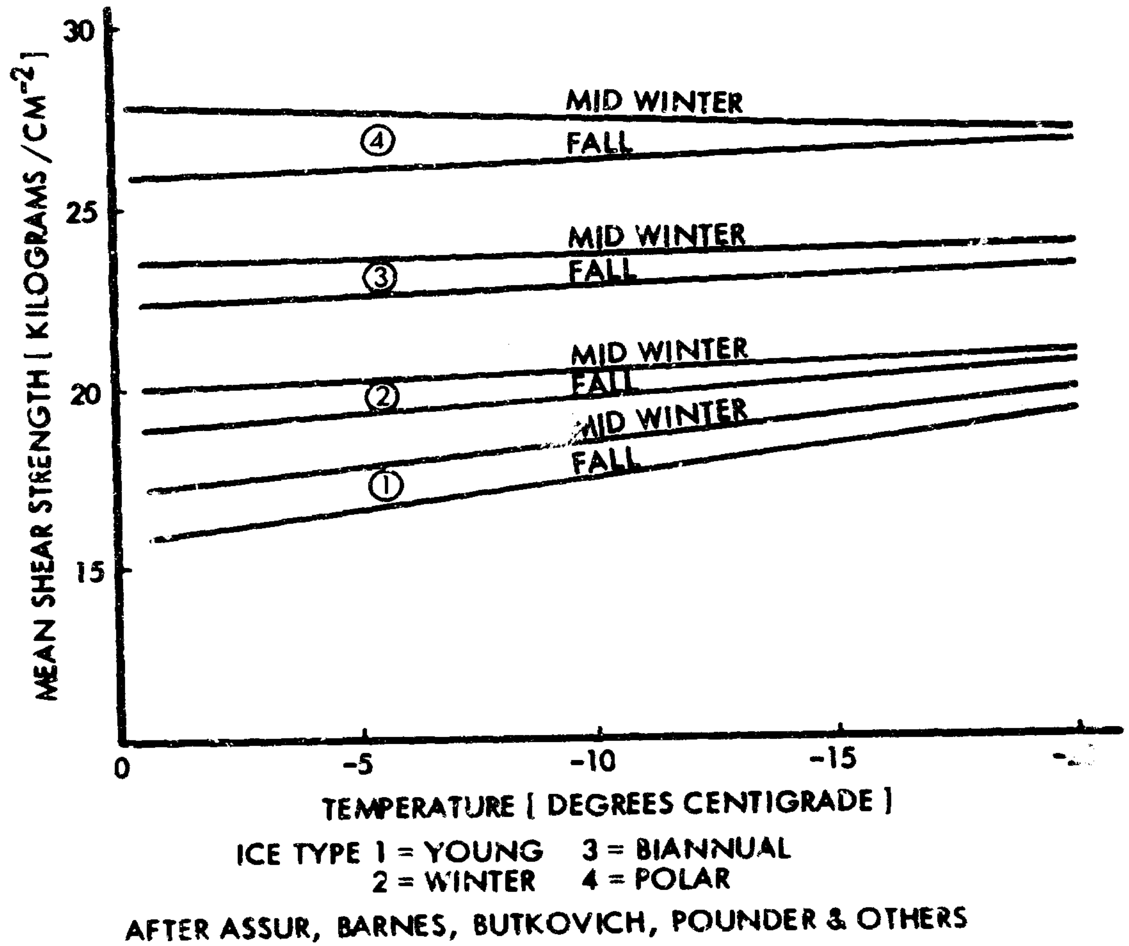


Figure 5-5: SHEAR STRENGTH FOR MAJOR ARCTIC SEA ICE TYPES

For use in systems design, Figure 5-6 considers ring tensile strength for the four major types of ice expected in the arctic basin. The young ice has a quite low strength, and the others progress in strength. The early fall types are the weaker in all cases, and warmer ice is weaker than colder ice. The threshold between warm and cold ice is -10°C for a given salt fraction. For ice which is below -20°C, the strength would change more rapidly than shown in the figure. (References 2, 5, 14, 17, 22, 27, 32, 35, 43, 47, 51, and 52)

5.2.9.7 Rate of Creep of Sea Ice

It is sometimes necessary to understand the rate at which a viscoelastic material such as ice will creep. Figure 5-7 is presented to give some approximation of what to expect. The creep rate is effectively the minimum slope of a strain-time curve and is plotted in pounds per square inch versus inches per inch per minute x 10^{-5}. These creep values are approximations. (References 2, 5, 9, 10, 14, 15, 18, 21, 27, 29, 36, 41, 44, and 47)

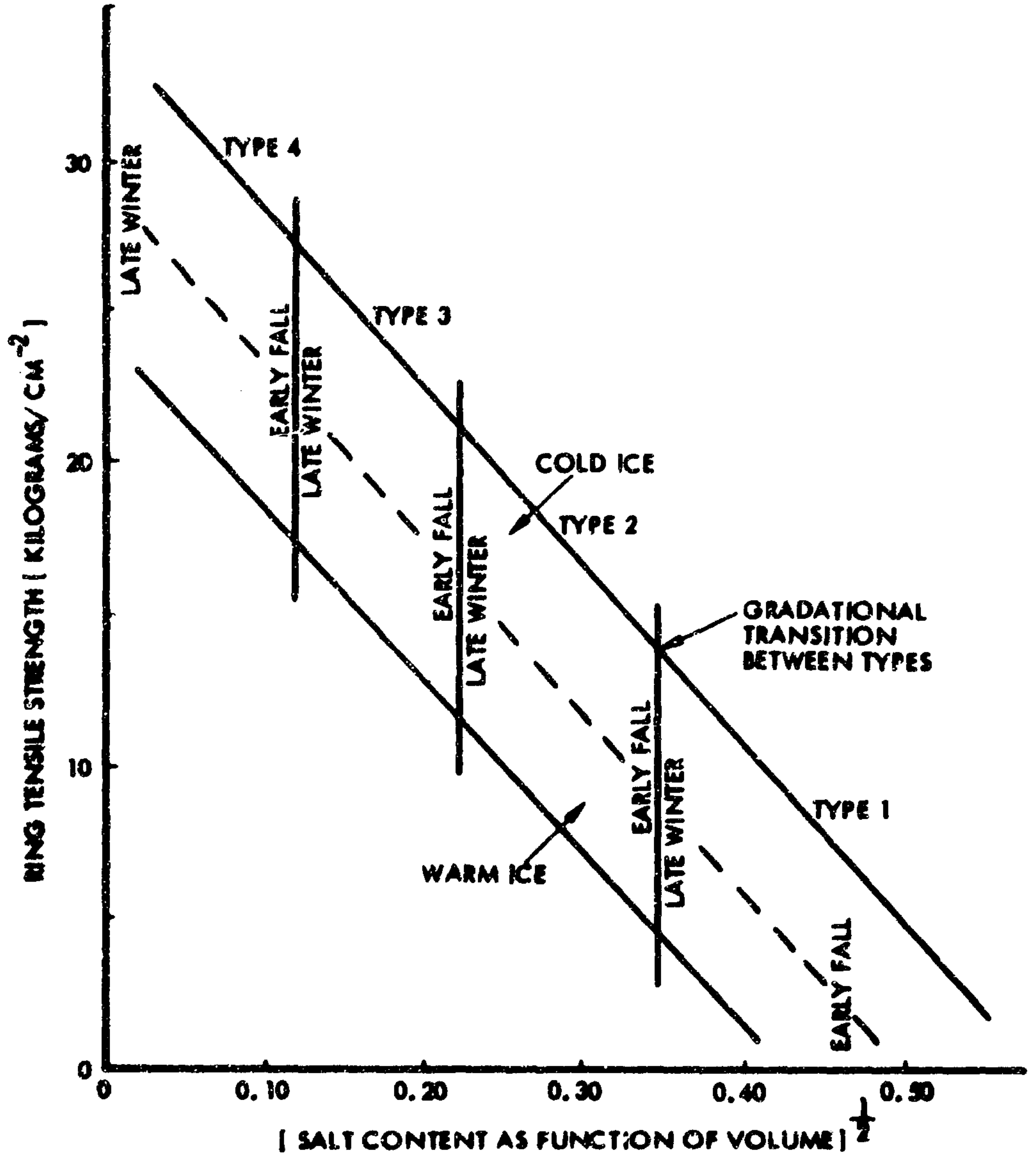
5.2.9.8 Other Properties

A number of special properties could be considered, such as permeability, friction, albedo, and adhesiveness. Permeability is discussed under the section on snow because it is significant to water conduction through snow cover to ice surface. Friction is also considered in the section on snow because most of the arctic ice is snow covered. Albedo is discussed in Section 9.1.

The adhesive properties of ice need a great deal of study, but some information can be presented. Substances with which water forms a large contact angle; however, contact angle is only a guide to adhesion to ice. For a general guide a lowering of temperature and salinity cause an increase in adhesive strength. Figure 5-8 presents expected adhesive strength for the four major ice types as a function of temperature. (References 1, 3, 4, 5, 15, 43, and 50)

5.2.10 <u>Land Ice</u>

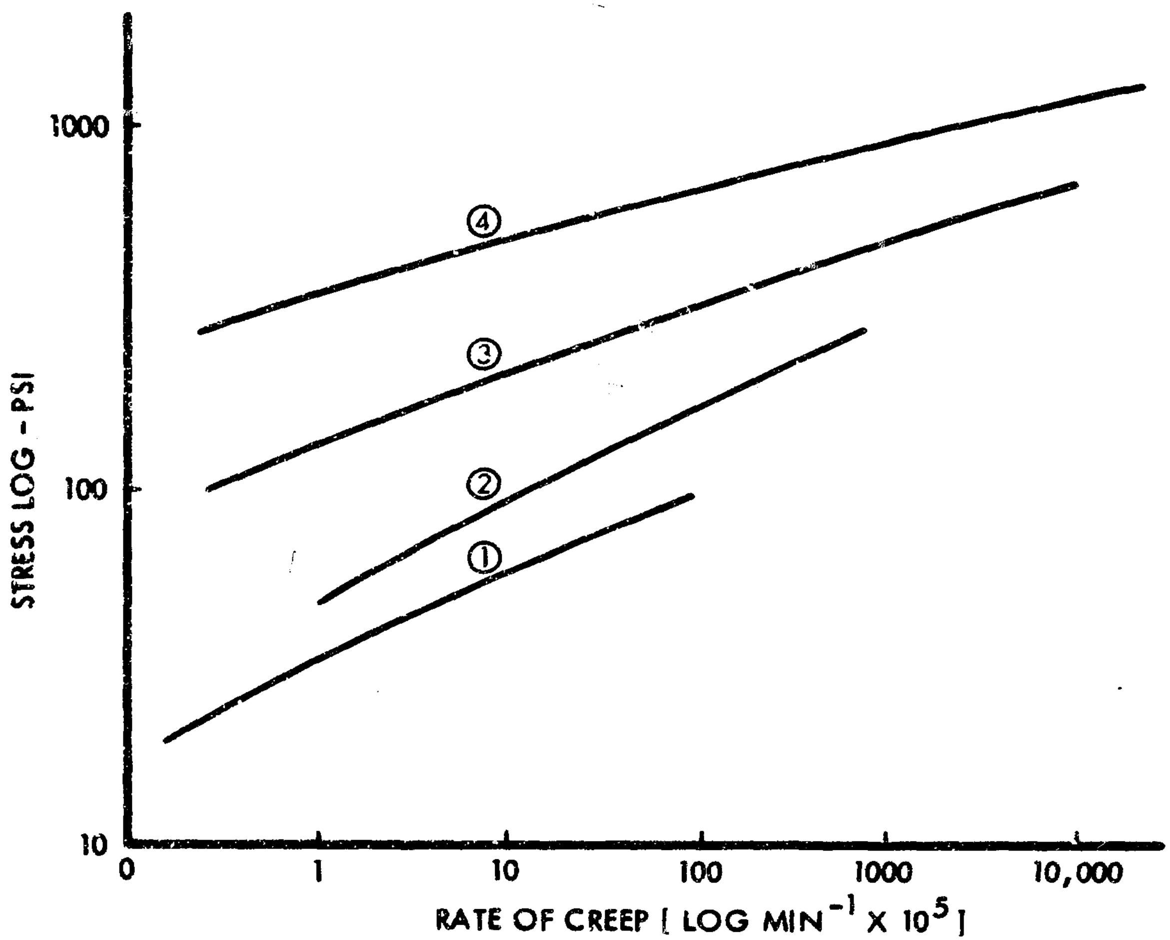
Land ice that drifts out into the basin has not been considered in the specific discussion of mechanical properties. Data is available for glacier ice, and studies have been conducted on floating ice islands. However, all forms of land ice have their own complexity because they were not made from salt water. Such ice has been subject to pressure loading and densification as snow fields that turn to ice under pressure from the surface snow and by metamorphic aging. The crystalline structure is therefore different than salt ice and thus all the mechanical properties are different. For mechanical property considerations these land ices are much stronger than any of the other four types considered.



ICE TYPE 1 = YOUNG 3 = BIANNUAL COLD ICE = -10°C TO -20°C
2 = WINTER 4 = POLAR WARM ICE = 0°C TO -10°C

AFTER - BUTKOVICH, BARNES, ASSUR, LANGELEBEN AND OTHERS

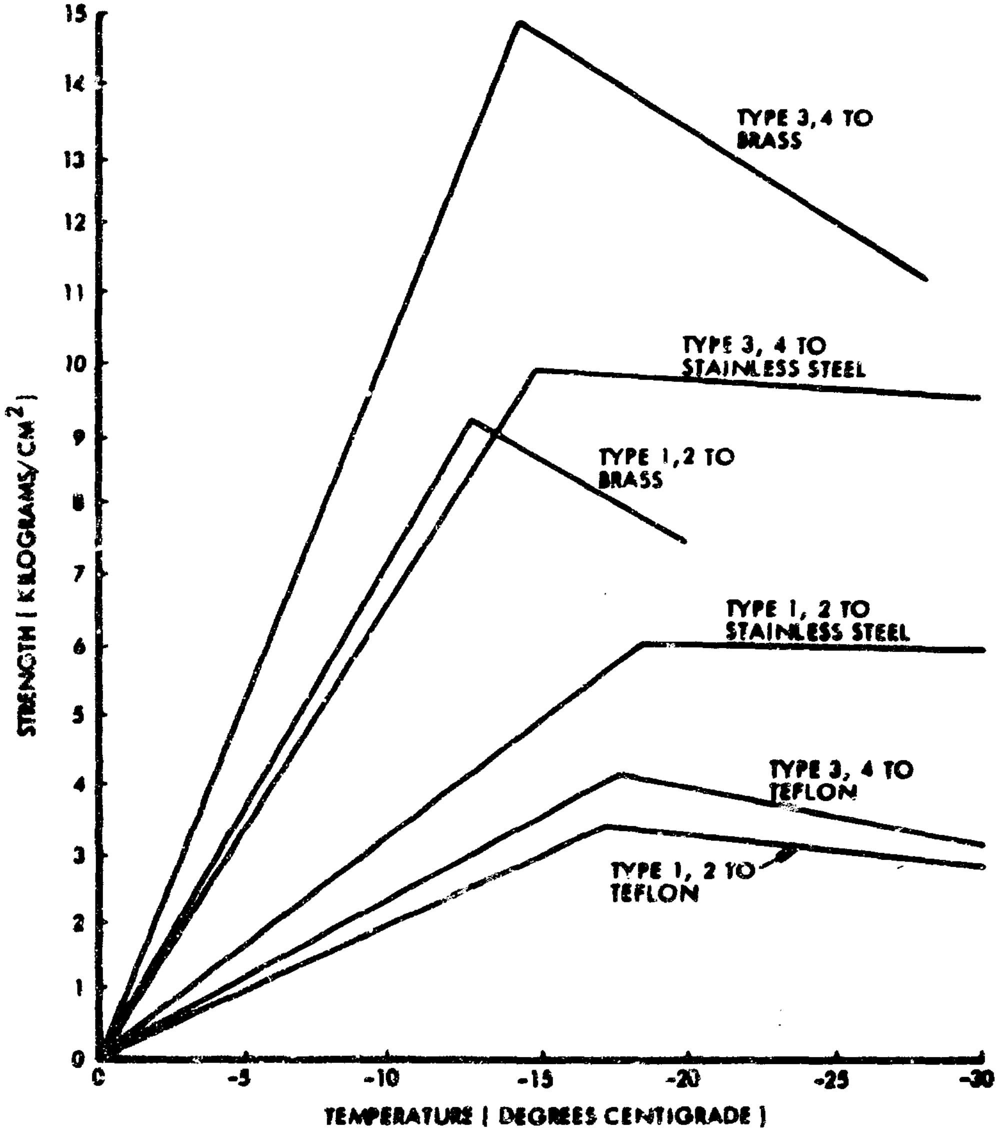
Figure 5-6: RING TENSILE STRENGTH OF ARCTIC SEA ICE



ICE TYPE 1 = YOUNG 3 = BIANNUAL
2 = WINTER 4 = POLAR PACK

CURVES TAKEN FOR APPROXIMATELY -10°C AFTER VARIOUS SOURCES

Figure 5-7: COMPRESSIVE CREEP RATE FOR MAJOR ARCTIC SEA ICE TYPES



ICE TYPE 1 = YOUNG 3 = BIANNUAL
2 = WINTER 4 = POLAR PACK

AFTER - VARIOUS SOURCES, FUNAI, GLEN, GRAYSTONE, JELLINCK, WEEKS, AND OTHERS

Figure 5-8: ADHESIVE STRENGTH VS TEMPERATURE FOR ARCTIC SEA ICE TYPES

5.2.11 Geomorphology of Polar Ice

5.2.11.1 General Considerations

Ice can be considered on the basis of its surface configuration. Weathering and erosional processes are appraised and thus mechanical properties are illustrated. In order to relate to the mechanical properties previously reviewed it is necessary to define the processes in terms of the five ice types.

5.2.11.2 Weathering

The four directly produced sea ice types can be considered as being similar to sedimentary rock. This analogy seems appropriate because of the mode by which sea ice freezes and thaws.

Weathering proceeds when salt solute interbeds between the polygonal ice plate layers and the air voids enlarge in the form of cells and tubes during melting. The analogy can be carried further in that the sea ice appears similar to a sedimentary rock which is weathering in an arid environment. The differential weathering is related to the degree of structural integrity of the various anisotropic ice layers. It also means that the weathering process is mainly mechanical in nature, with weathering agents being temperature, wind, or wave action.

An increase in temperature of 10 degrees permits water to move upward or downward in the ice profile and laterally between ice layers. The water can then refreeze and cause expansion between the ice grains and shearing along established shear planes. In this way pieces of the ice sheet break off from the parent ice.

Waves and wind loosen grains and sculpture the ice. They also provide the energy to rub ice against ice. The abrasion process is most effective if the ice grains are large-sized polygrains and there is appreciable void volume between the grains.

5.2.11.3 Erosion

Once the parent ice has been broken to some degree, the processes of erosion are wind and water action under the influence of gravity.

The production of water from wet snow fall, ice pellet storms, or rain provide water to the upper surface of the ice. This water percolates through the snow blanket and permeates the ice in available voids or flows along cracks, resulting in the gradual leveling of ridges. Water can

also move upward in the ice profile by capillary action through the voids, tubes, and cells in the ice. The water is then available in the upper layers of the ice to wash material downslope or saturate loose ice or snow at the surface of the pack and cause slumping or slippage of loose segments of ice.

The wind sculptures the coarse textured portions of the upper segments of the ice sheet and thus moves material either laterally across the ice or gradually avalances the bulked material down the slopes of the ice ridges.

5.2.11.4 Ridge Types

Because of the different mechanical strengths of the various ice types, one will weather and erode differently from another. Figure 5-9 illustrates forms of ice relief and depicts the kinds of ice types they contain.

Case A: Simpl Ridge---This is one of the simplest ridge types. The core is generally biannual ice, and the outer or upper surface is winter ice. The winter ice varies considerably in strength, depending on the time of the season. The sloping sides develop by water percolation erosion, which increases as the surface pores, and salt solute tubes increase surface water flow. The ridge crest is relatively weak, and the upper 1 to 2 feet are highly subject to erosion under a shearing or compression loading. On a volume basis, the ridge generally is divided 50%-50% or 40%-60% for Types 2 and 3 ice.

Case B: Compound Ridge---This is a ridge of relatively low height. Due to the percolated water, which tends to accumulate between the ridge heights (above Type 3 ice in the Figure 5-9), the strength of the inner slopes of the ridges are degraded. The strength of the core of the ridge is also degraded because it contains crushed ice and ice of high permeability. The basic mechanics of formation is such that there is folding and overturning of the ice layers. This ridge has only moderate strength and is of a viscous nature.

Case C: Faulted Complex Ridge---This ridge resembles a mountain belt with a series of faulted layers lying next to each other. Since this type tends to form in zones of strong ice it is basically a strong material. When the ridge floats into a warm zone or the weather moderates, weathering and erosion begin along the fault planes. At this point erosion and degradation is quite dependent upon the amount of salt in and porosity of the ice layers. The initial strength is greatly dependent upon the amount of crushing during formation.

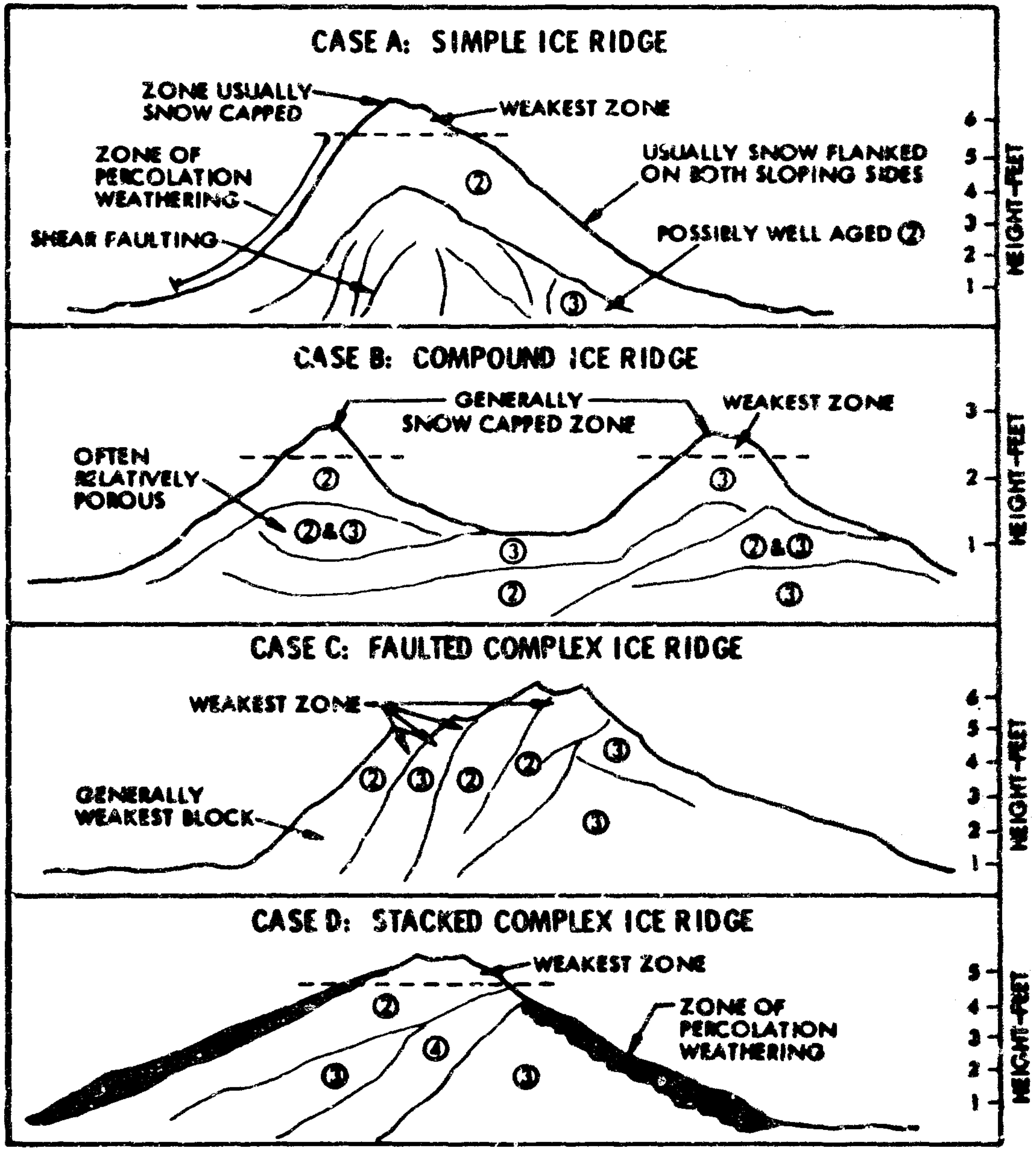
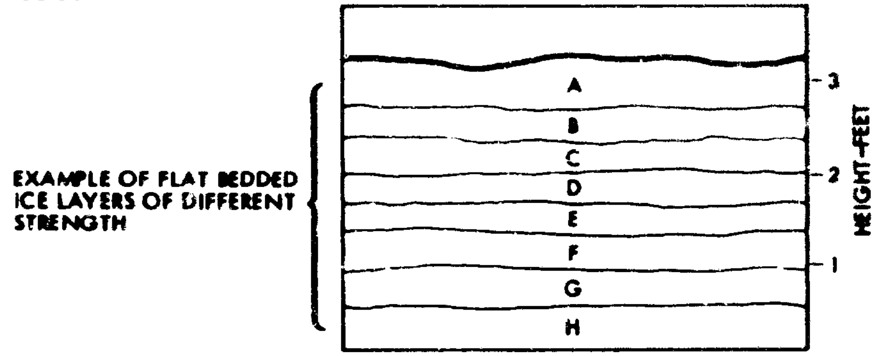
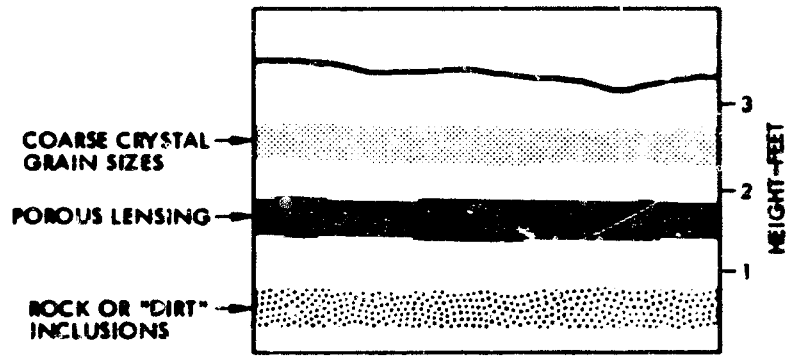


Figure 5-9: SPECIFIC RIDGE TYPES

CASE E: DIFFERENTIAL WEATHERING ICE BLOCKS



CASE F: LAYERED RIDGE SUBJECT TO WIND SCULPTURE



CASE G: TYPES OF ROCK/BOULDER/COBBLE INCLUSION

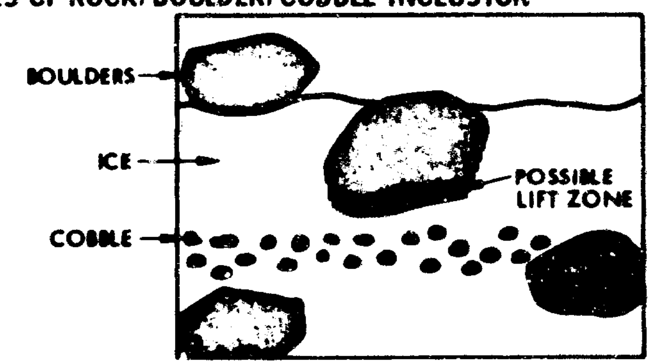


Figure 5-9: SPECIFIC RIDGE TYPES (CONT)

Case D: Stacked Complex Ridge---This type is usually not as strong as that of Case C, even though it may contain older and more metamorphosed ice. The upper zone is much weaker than C and subject to erosion under shearing or compression loading. During old age the slopes degrade rapidly by percolation and wind erosion. This ridge is only moderately strong.

Case E: Differential Weathering Blocks---The figure illustrates a phenomena noted by many travelers in the arctic basin. Because ice is an anisotropic material in nature, its dissimilarities are accentuated by erosion. The morphology reflects the nature of the hardness and general strength of the ice block. By observing such ice blocks, the ice strength can be assessed in a specific geographic area. Since the ice is eroding under wave action, the degree is related to the amount of salt content, porosity, degree of metamorphic action, and thickness of the various layers.

Case F: Ridge, Berg, or Block Subject to Wind Sculpture---Figure 5-9 illustrates the relationship of ice makeup and wind erosion. If the ice contains bands of large coarse-grained polycrystals, very porous lensing, and bands of entrained rock or other particulate matter, these are the zones of weakness which are sensitive to wind erosion. As in Case E the important consideration is that the ice is anisotropic. Young ice has higher porosity than late winter ice or ice that has less porosity than warm-temperature ice. Rock- or dirt-banded ice either has come from a continental margin or is still in the vicinity of some soil source such as shallow ocean bottom. If the ice is in the polar pack, it has had considerable metamorphic aging. It should thus be stronger than surrounding polar ice. The coarseness of ice depends upon the pressure, temperature, and moisture environment of the ice during the metamorphic process.

Case G: Rock/Boulder/Cobble Inclusions---As shown, "rock" can appear at all locations on top of, within, or under the ice. Most of the larger rocks present on a floating ice sheet, such as the polar pack, is material that has been rafted from the land. Such rock is associated with ice islands and, on occasion, bergs. Cobble generally comes from similar sources. Fine-grained material can come from a variety of sources: rafting; entrainment by freezing on the under side of a pack in a shallow bottom area with a high degree of turbidity; and horizontal near-surface storms near the land edges of a pack.

At the surface a large rock acts as a trap for snow, is a good base for refreezing of water (rock with an ice cap), and is an initiator for ice heaving. Entrained in the pack, the rock serves as an initiator for faulting and ice breakup. Fine-grained material, on the other hand, tends to become an integrated part of the ice. If the ice is at near-freezing temperatures, the fine-grained rocks (sand, silts) aid in melting and degrade the structural properties. If the fines are in a cold-temperature, aged ice, the ice will increase in strength to an extent

depending on the volume of fines present. The strongest ice occurs when the fines are interbedded in narrow layers with a cold-temperature ice.

Table 5-5 summarizes geomorphic ice types and their mechanical properties.

Table 5-5: GEOMORPHIC ICE TYPES AND MECHANICAL PROPERTIES

Geomorphic Ice Type	Average Mechanical Strength Evaluation	Remarks
Case A	Moderate to strong	Top of ridge weak; degenerates at a generally rapid rate.
Case B	Moderate or less	Top of ridge weak; entire series tends to slump and form low ridge relief.
Case C	Strong	Ridge rather stable; keeps structural character over extended time periods.
Case D	Moderate to strong	Top of ridge relatively weak, subject to slumping, shearing, and some shattering. Strength is greatly dependent on the portion of volume of Types 2, 3, or 4 ice in the ridge.
Case E	Variable (moderate)	A good visual indicator of complexity of ice types present and the total strength of the pack.
Case F	---	Similar to E.
Case G	Variable	Strength greatly dependent on degree of fines of particulate matter and degree entrained banding.

5.2.12 Postulated Ice Types and Geographic Distribution

Figures 5-10 and 5-11 show postulated types of ice and their percentage distribution along a transect across the arctic basin during the summer period (maximum thawed area) and the winter period (maximum ice coverage). It must be recognized that, since the ice is in constant motion, any given geographic sector of the basin has a variety of ice types regardless of the seasonal period.

5.3 MECHANICAL PROPERTIES OF SNOW ON THE POLAR ICE PACK

5.3.1 General Comments

The snow that covers the polar pack is an important environmental component. It directly affects trafficability, and has significance in both its electrical and heat-transfer characteristics.

Mechanical studies of snow on arctic sea ice are almost nonexistent. It is important, however, to attempt to sort out as much about the nature of this snow as knowledgeable comparison make possible.

5.3.2 Snow Types

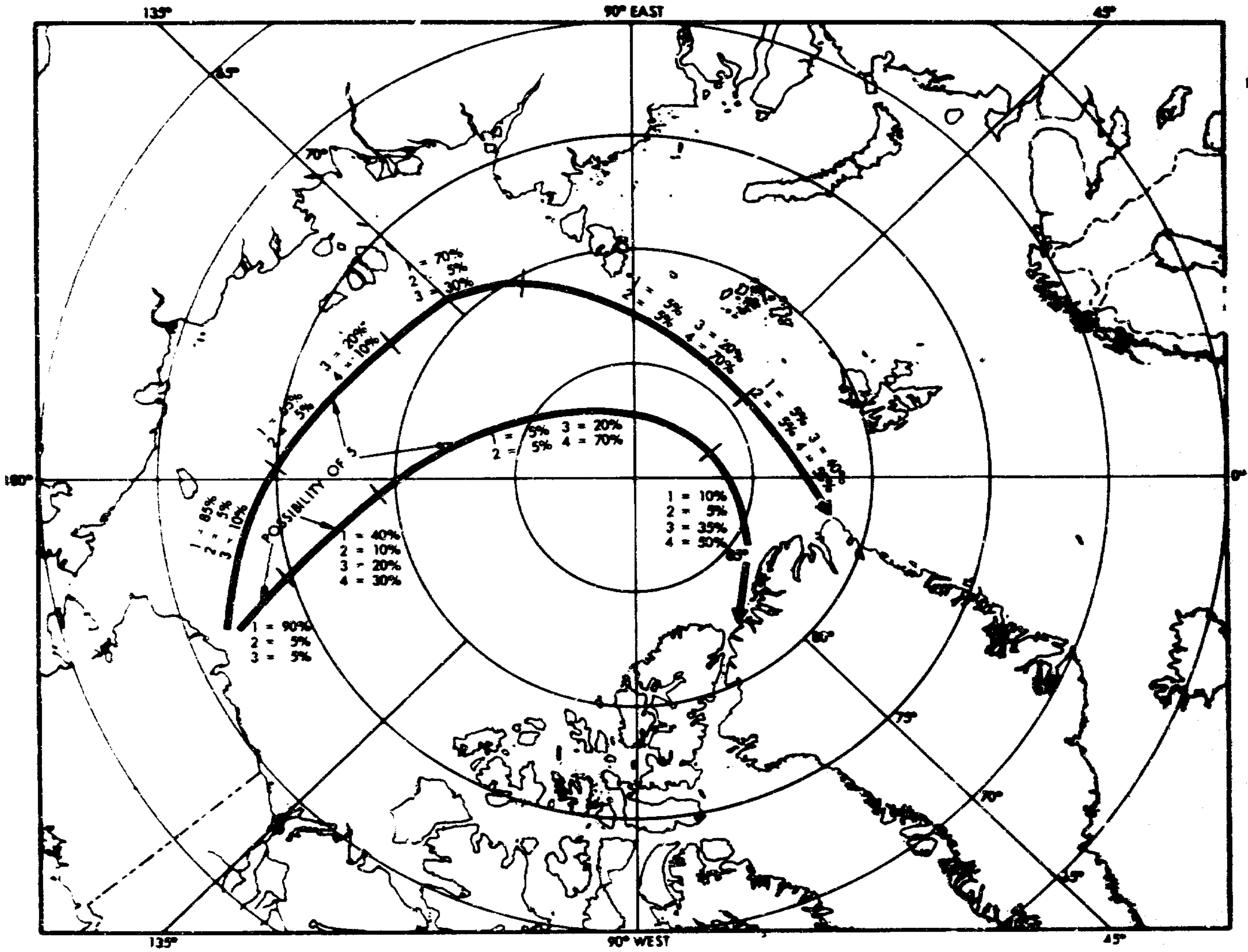
There are a number of types of snow found in nature. If all types were analyzed, assessment for mechanical properties would be very difficult; however, it is possible to reduce these to a limited number of types which are representative of the polar basin. The presentation here is a simple three-division classification. This classification was so chosen that further field research will not conflict with this data, but simply increase its accuracy. (References 58, 61, 68, 72, 73, 79, 83, and 86)

The three types are:

1) Liquid---Snow of average size flakes; and in which snow becomes moist after deposition and snow-pack temperatures tend toward uniformity through the profile.

2) Destructive---Snow in which the crystals remain of small size (generally between 0.25 to 1.0 mm in diameter) and the grains become well rounded and lose most, if not all of their original crystal shape.

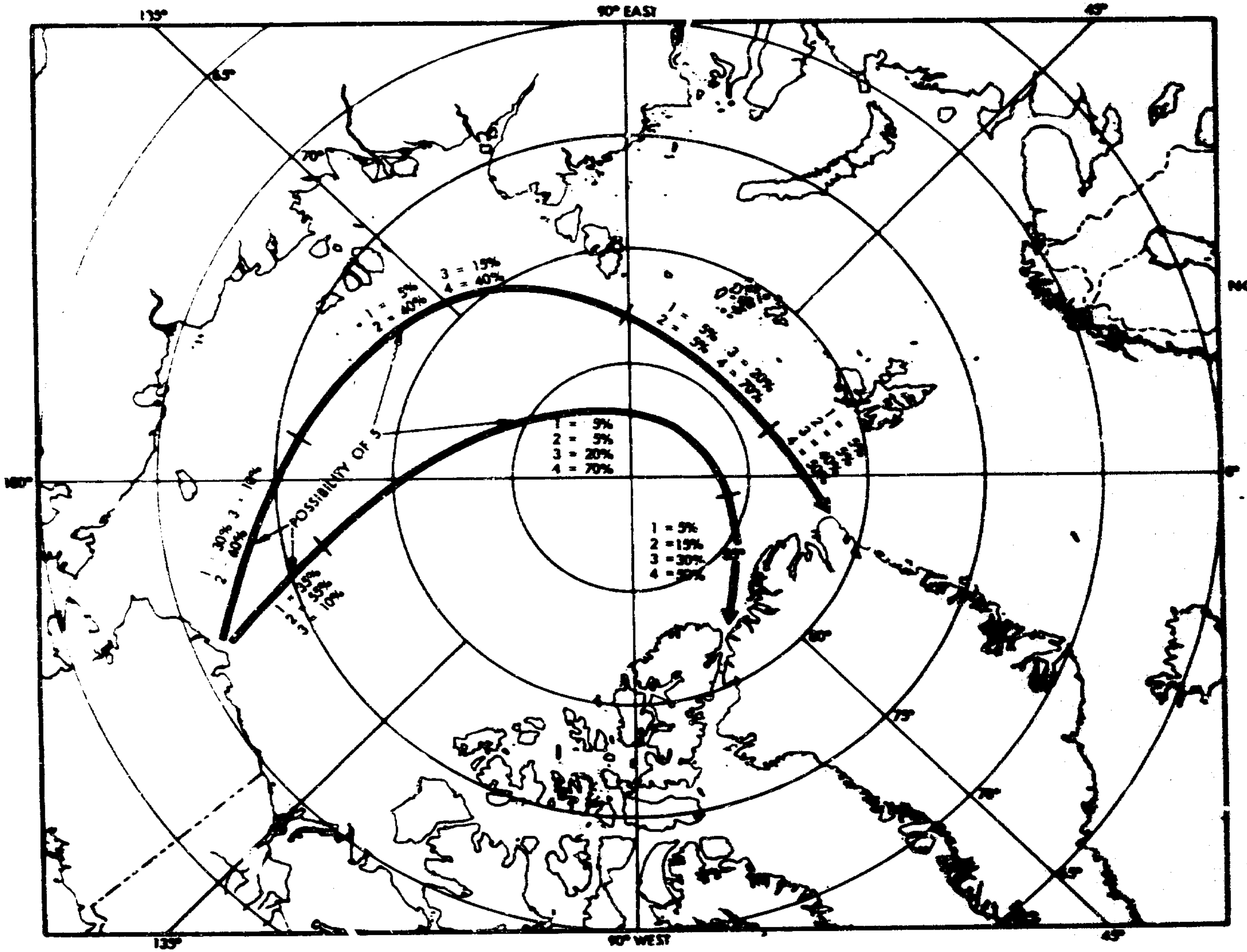
3) Constructive---Snow in which the crystals grow to sizes over 1.0 to 2.0 mm in diameter, and which is relatively dry.



NOTE:

OPEN WATER IS NOT CONSIDERED, PERCENTAGES ARE ON AN ASSUMED PERCENTAGE OF ACTUAL ICE IN AN AREA.

Figure 5-10: POSTULATED EXAMPLE OF EXPECTED ICE TYPE AND PERCENTAGE OF AREA SUMMER-EARLY FALL



NOTE: OPEN WATER IS NOT CONSIDERED, PERCENTAGES ARE ON AN ASSUMED PERCENTAGE OF ACTUAL ICE IN AN AREA.

Figure 5-11: POSTULATED EXAMPLE OF EXPECTED ICE TYPE AND PERCENTAGE OF AREA WINTER-MIDSPRING SEASON

There are a number of ways in which to classify the snow on sea ice in relation to mechanical properties. For example, snow termed "pressure type" is generally associated with arctic polar regions, but is a type that slowly changes into glacier ice. Such overland types are not important for the arctic seas. The three important types are wet snow, cold metamorphozed snow, and relatively dry hoar as might exist under certain meteorological conditions. (References 76, 80, 83, 85, and 86)

5.3.3 Basic Mechanical Nature of Snow Types

5.3.3.1 Liquid Snow

Liquid snow is one of the most common types to be expected on the basin waters. This is a viscous snow pack, which generally begins as snowfall with flakes of approximately 1-mm diameter, or under the appropriate meteorological condition as some form of pellet. The snow is subject to melt or ablation and refreezing. The grains grow large, forming aggregates of polycrystal clusters, with the grains oriented their long axes in relation to the flow of liquid water down through the snow pack or percolation along elevation contours such as on the sides of ice ridges. This type of snow is very temperature dependent in relation to its physical properties.

At warm temperatures, near the freezing point, the material becomes plastic and reacts in a viscoelastic way. At cold temperatures the material is strong and reacts in a brittle fashion as many metals do.

5.3.3.2 Destructive Snow

In the destructive type, the crystals remain 1 mm or less in diameter. The individual crystals do not have strong intergranular bonds, even though the grains become well rounded and lose most of their original shape. In the center of the polar ice pack such snow can last for more than one winter season and slowly froms dense granular masses which are able to draw up capillary water from the ice pack below the snow surface. The result is a semirigid beam-like cover. Such a surface provides an ideal traffic base. If water is not readily available from the ice below, the pack becomes a loose agglomeration of material without strength.

5.3.3.3 Constructive Snow

Constructive snow is the least plentiful type in the basin. The large snow grains have weak intergranular bonds; the result is a rather viscous and low-strength material. The meteorological conditions required for good hoar are usually not present, but such material can develop

internally within the snow pack profile. If present, it is found below ice layers within the snow, or just above the surface of the ice if the latter is dry. Such snow can be deceptively weak, because of the wet ice crust that may be present on the surface.

5.3.4 Geographic Location

Table 5-6 shows possible snow locations by type.

Table 5-6: FORECAST OCCURRENCE OF SNOW TYPES

Location	Season			Remarks
	Fall	Winter	Spring	
Barents Sea	1	1,2	1,2	Northern and interior part.
Kara Sea	1,2	1,2	1,2	2 more probable present near land in winter.
Laptev Sea	1,2	1,2,3	1,2	
East Siberian Sea		1,2,3	1,2,3	A cold, almost continental area; colder to north.
Chukchi Sea	1,2	1,2	1,2	
Beaufort Sea	1,2	1,2	1,2	Wet Snow Basin.
North of Canadian Arctic Islands	1,2	1,2,3	1,2,(3)	
Interior Canadian Portion Arctic Basin	1,2	1,2,(3)	1,2,(3)	These areas can have Type 3 in ridges or other heights
Eurasian Portion Arctic Basin	1,2	1,2,(3)	1,2,(3)	

NOTF: 1 = Liquid snow; 2 = Destructive snow; 3 = Constructive snow.

Ice islands can have all three types.

References 68, 70, 71, 72, 73, 77, and 82

5.3.5 Major Mechanical Properties

5.3.5.1 Young's Modulus

Since there is considerable variation in snow properties between the liquid (Type 1) and the dry constructive (Type 3), a range is shown for Young's Modulus. As the snow ages there is an increase in the modulus (Figure 5-12). The plot shows the range of change in E through the density change expected. The modulus is dependent upon density and metamorphic aging. In addition, there is approximately a 0.10×10^{10} change between the freezing point and -50°C. In practice, if a system is to work under the colder temperatures the increase in E should be applied. (References 56, 60, 62, 64, 67, 72, and 76)

5.3.5.2 Ultimate Strength

To measure ultimate strength of snow, it is necessary for loading to occur rapidly so that failure takes place in an elastic condition. In most recommended testing this is 500 $gm/cm^2/sec$. The strength of snow is basically dependent on temperature and density. Figure 5-13 is a plot of change in ultimate strength versus change in temperature. The plot shows a range to account for the effects of rates of temperature lowering and influence of metamorphic aging. (References 61, 62, 64, 69, 71, 78, 83, 84, and 85)

5.3.5.3 Unconfined Compressive Strength

An important mechanical property of snow is its unconfined compressive strength. In practice, various researchers have conducted testing by crushing cylindrical specimens with some form of rapid and uniform loading. The laboratory testing generally consider unconfined compression versus density at a given temperature such as -10°C, a standard laboratory temperature. (References 61, 71, 75, 78, 83, 84, 85, and 86)

It is possible to plot the three snow types versus density for a given temperature range. Field observations indicate that compression data is reliable between -5 to -20°C. For temperatures lower than -20°C, the snow samples become stronger for lower densities. These curves are shown in Figure 5-14. The strongest snow is the destructive type. The liquid type is less strong, but becomes stronger if the void space between the grains is partially filled with frozen water. The least strong is the constructive type, for which it is questionable to consider densities much over 0.625 gm/cm^3. To make the data more useful, line intersects have been drawn across the curves to show the data by seasonal periods. The values on the line intersects are averages that can be expected for one of the three snow types during the given season. If

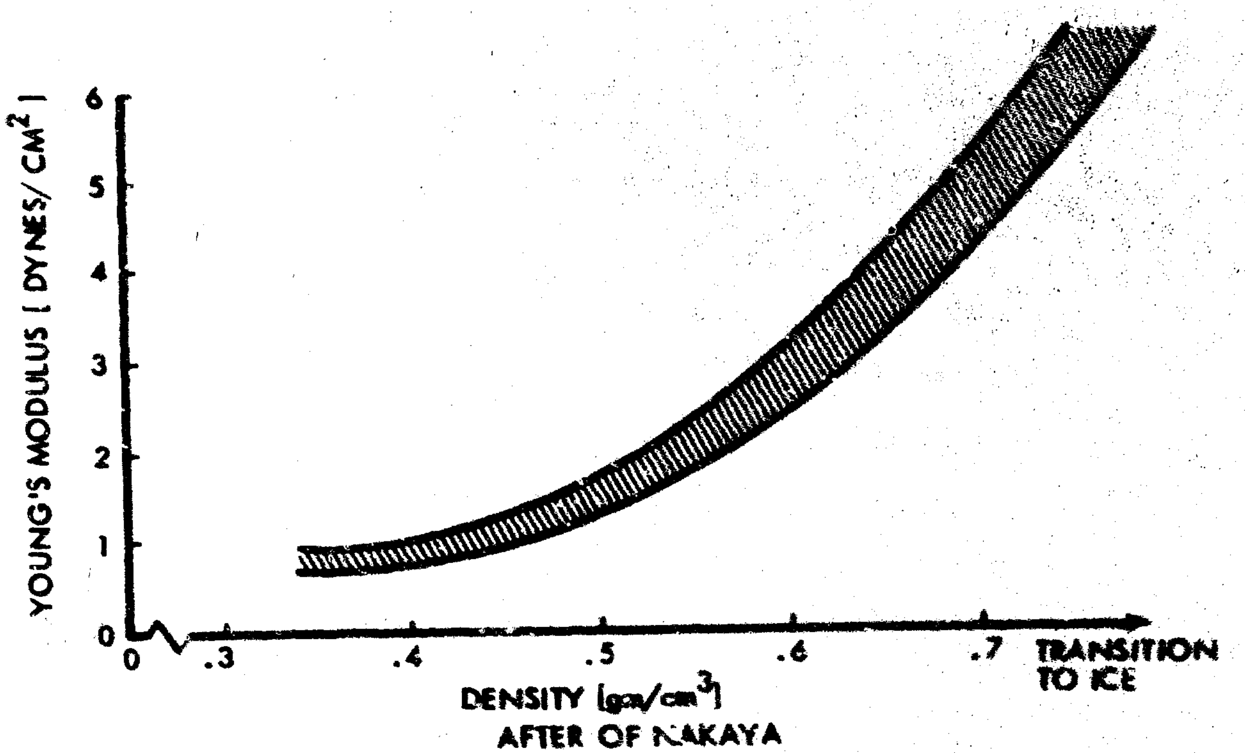
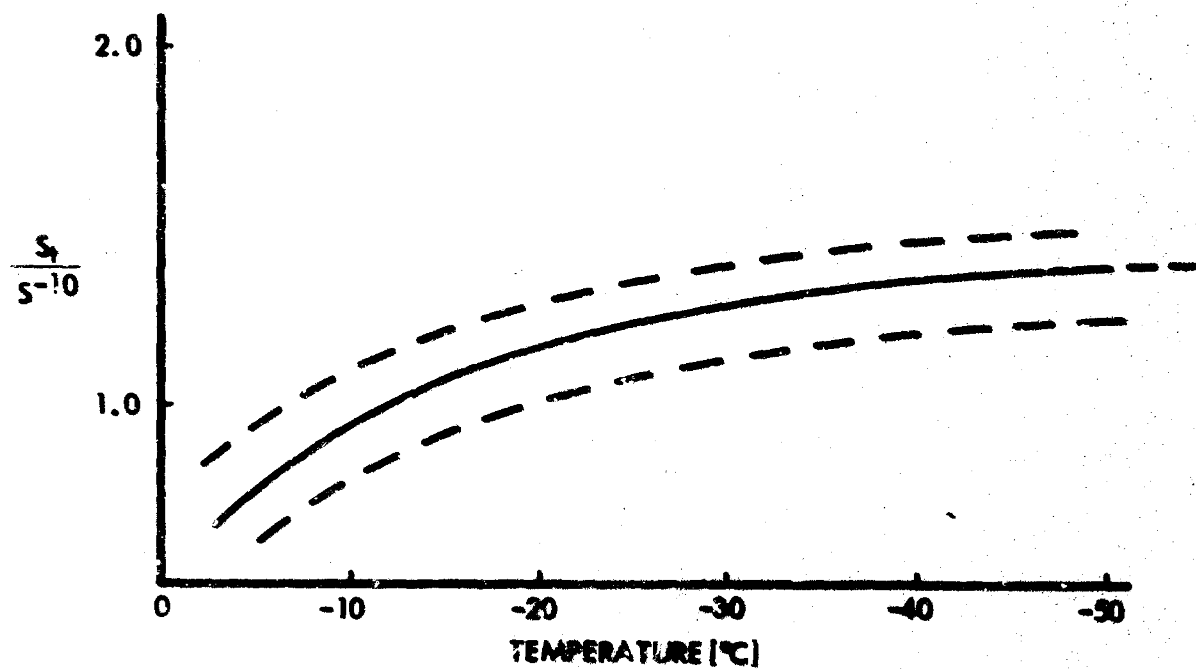


Figure 5-12: DYNAMIC YOUNG'S MODULUS



$S \alpha \sqrt[6]{t}$, S = ULTIMATE STRENGTH
t = NUMBER OF DEGREES C AFTER BUTKOVICH

Figure 5-13: PLOT OF ULTIMATED STRENGTH vs TEMPERATURE

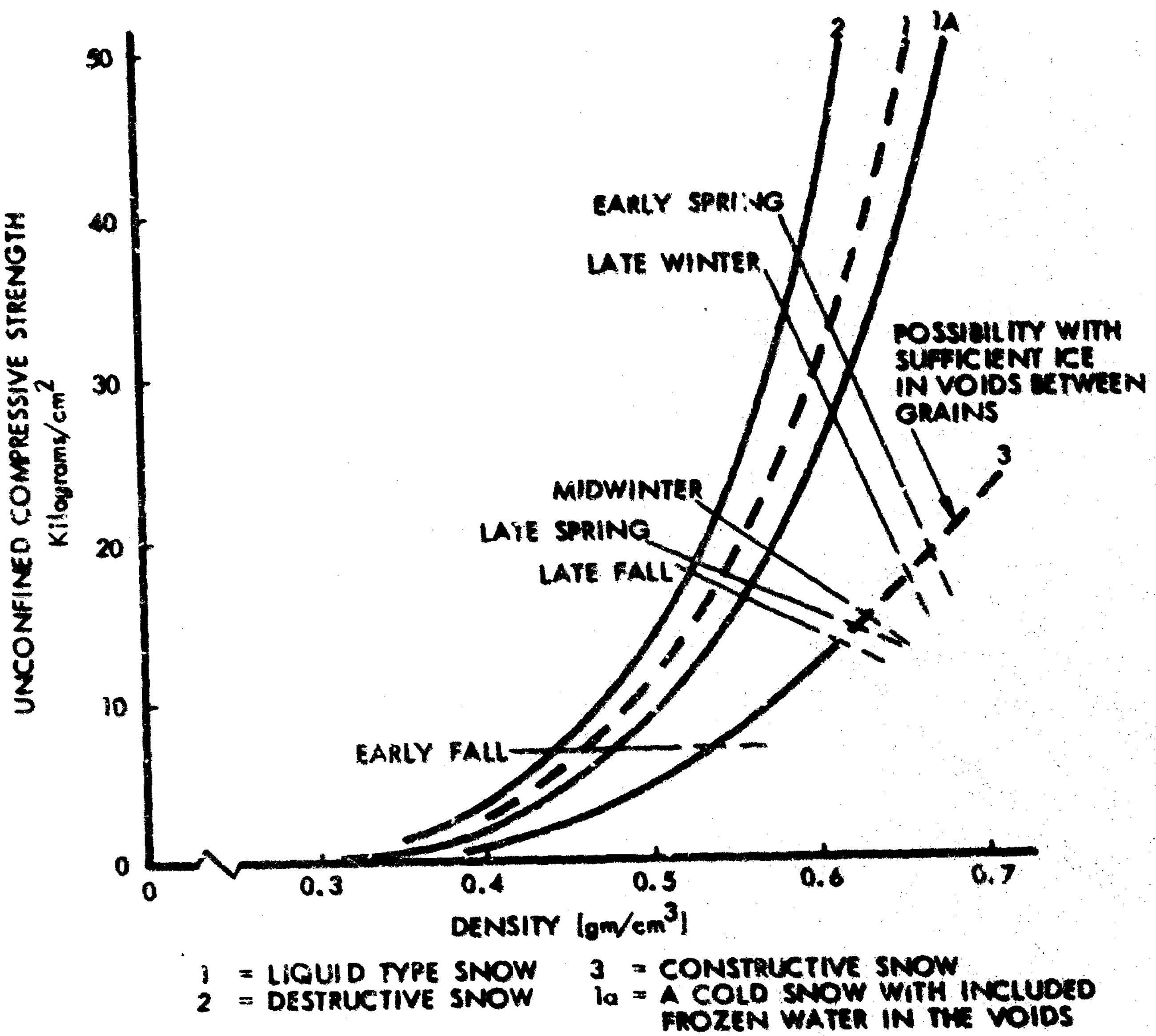


Figure 5-14: UNCONFINED COMPRESSIVE STRENGTH vs DENSITY

the working temperatures are quite low for extended periods (i.e., -50°C for a week), compression values should be increased by approximately 5%.

5.3.5.4 Tensile Strength

Tensile strength properties of snow are important but difficult to investigate. Snow does not lend itself to simple tension tests. Test have been made, however, by means of pressure applied normal to the axis of the snow grain and deposited profile.

As in unconfined compression, tensile estimates for snow types can be compared to density. The data shown in Figure 5-14 is for snow between -5 to -20°C. At temperatures lower than -20°C the snow becomes stronger for lower density values. It is suspected that at temperatures lower than approximately -50°C the snow could have tensile strengths which are less, or remain constant, for a given density. This would be the case if the voids between the grains contain little or no frozen water.

As shown in Figure 5-15, tensile values are approximately half of the amounts shown for unconfined compression, and threshold values are for densities greater than 0.4 gm/cm^3. The constructive snow type should have very low tensile strengths.

For extended periods of low ambient temperatures of -30 to -50°C, the tensile strengths for the liquid and dstructuve snow should be increased approximately 5%. (References 58, 61, 71, 72, 77, 83, 84, 85, and 86)

5.3.5.5 Shear Strength

Various types of shear tests have been investigated on snow including torsional and double shear. The shear strength for the three types of snow expected on polar basin sea ice is given in Figure 5-16. The material is shown as a band to account for variation in load application. The figure shows double shear plotted against density. As in compression and tension, an average working temperature range -5 to -20°C is assumed. Since the shear values of constructive snow are rather low, the plot presents a band from strong to weak. Three lines of intersection show the average values expected for fall, winter, and spring. This means that the values increase from fall to mid-winter and then decrease again until late spring. (References 59, 60, 63, 67, 70, 73, 83, 84, 85, and 86)

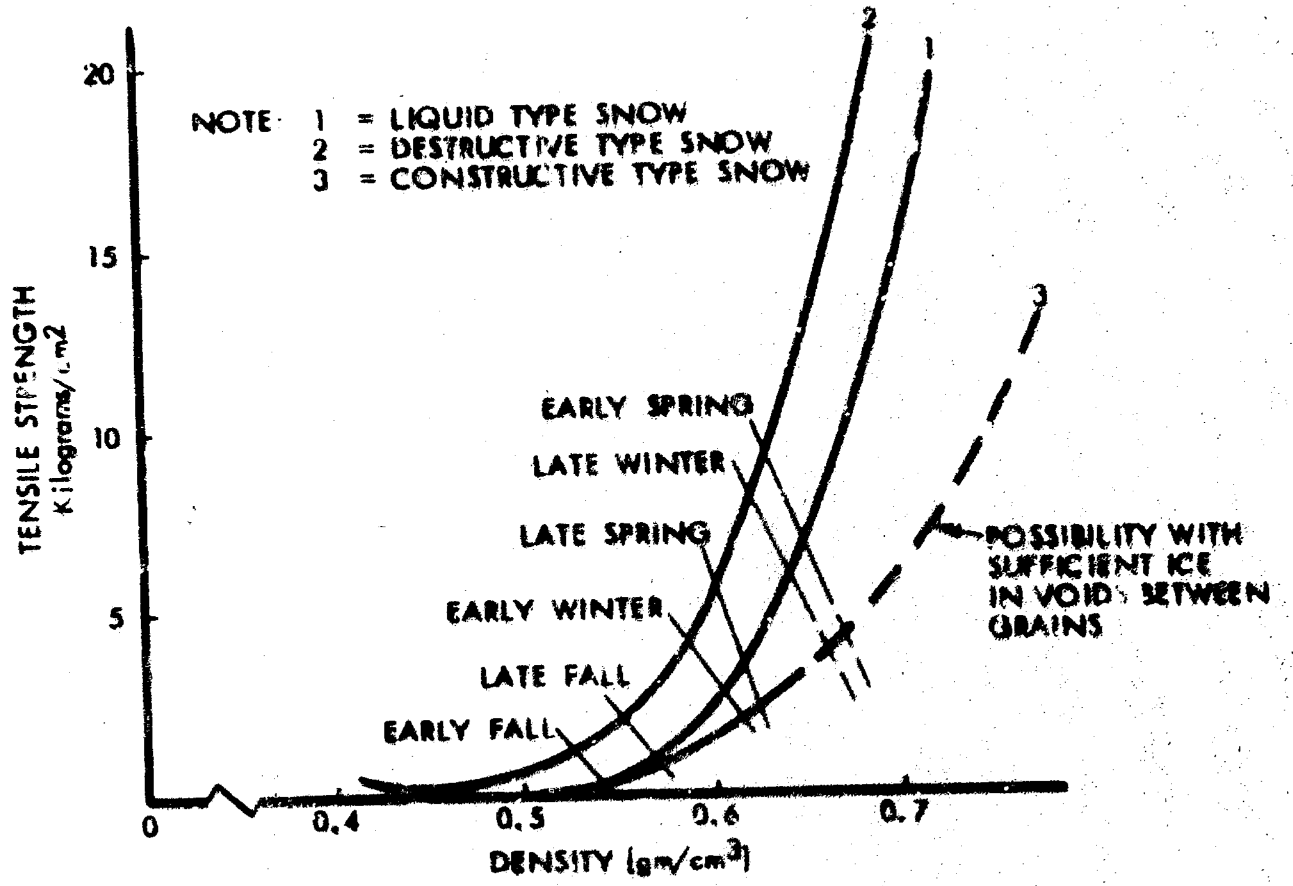
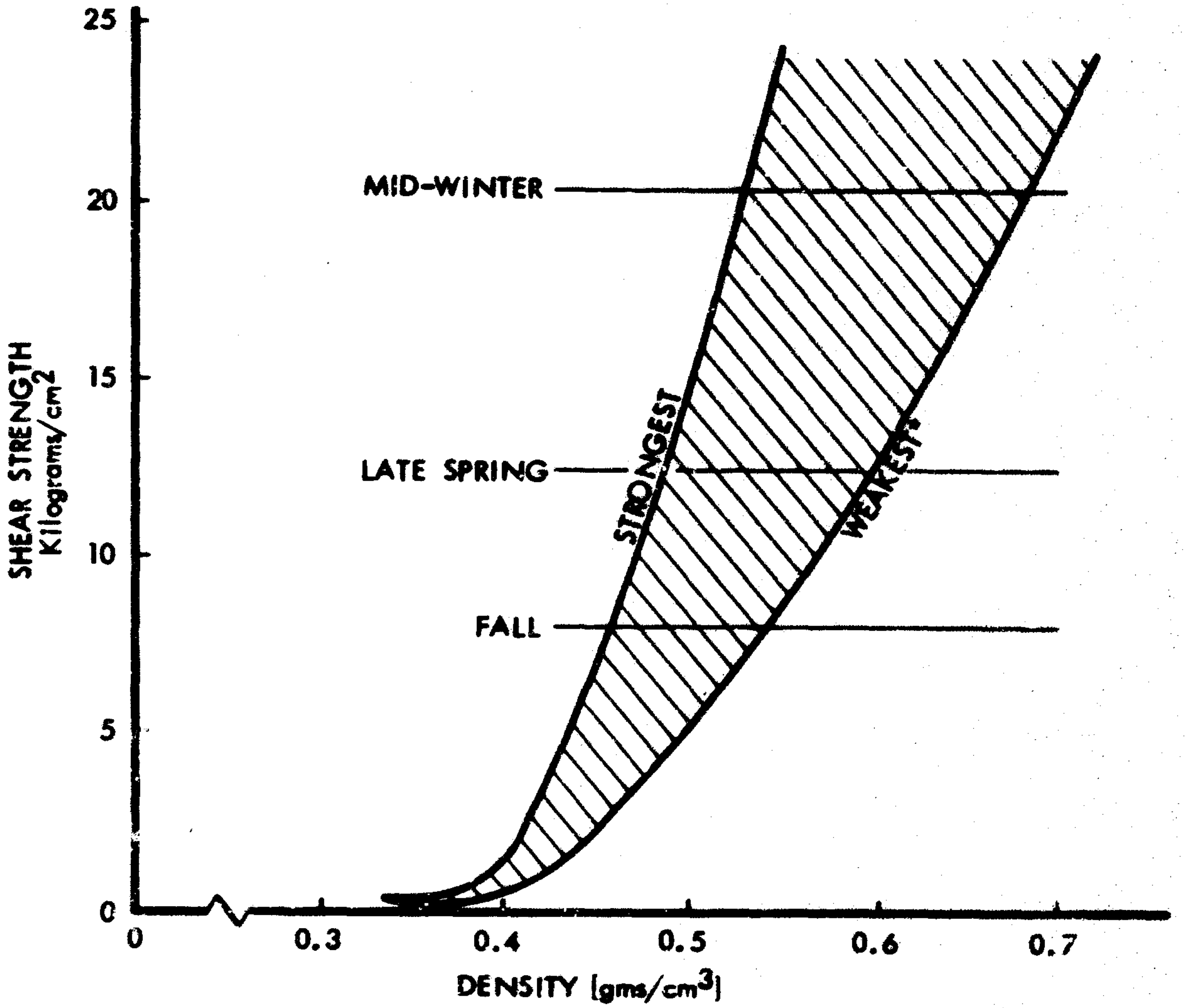


Figure 5-15: TENSILE STRENGTH vs DENSITY



*FOR THE WEAKER SNOWS [TOWARDS THE RIGHT IN THE CURVE] A HIGHER DENSITY IS REQUIRED TO OBTAIN THE SAME SHEAR STRENGTH.

Figure 5-16: UNCONFINED SHEAR vs DENSITY

5.3.6 Other Properties

5.3.6.1 Friction

For much higher tonnages than shown in Figure 5-17, the apparent coefficient of friction is influenced by the bearing pressure. For high speeds the coefficient of friction should remain relatively constant. As the aging metamorphism increases for old surface snow in the spring period, the coefficient should go up in areas which are relatively dry and where snow crystal grain sizes increase; however, for the wet snows the coefficients should remain relatively constant. The most important design factor is that sliding friction decreases as the temperature increases toward the freezing point as long as the snow remains relatively dry. (References 66, 70, 74, 77, 81, 84, 85, and 86)

5.3.6.2 Air Permeability

The relationship of porosity versus air permeability for three types of snow considered is shown in Figure 5-18. (References 59, 60, 70, 72, 73, 79, 80, 85, and 86)

5.3.7 Geomorphological Considerations

In addition to the standard mechanical properties of a snow cover, the snow in the arctic can be considered on the basis of its geomorphic character. This reflects the characteristics, origin, and development of the snow. These characteristics in turn depict traditional mechanical properties such as unconfined compression.

Considerable diversity is possible in the geomorphic nature of the snow cover over such a large geographic area, but there is need for a useful simplification. Accordingly, the major geomorphic types have been divided into six snow-cover types on flat ice and three snow-cover types in connection with ridging. The nine types are explained in terms of the three kinds of snow: liquid, destructive, and constructive.

The nine profiles discussed should not be considered as an ultimate; nevertheless, this technique is worthwhile as a means of relating the snow to engineering needs. (References 58, 59, 63, 64, 65, 67, 70, 77, 83, 84, 85, and 86)

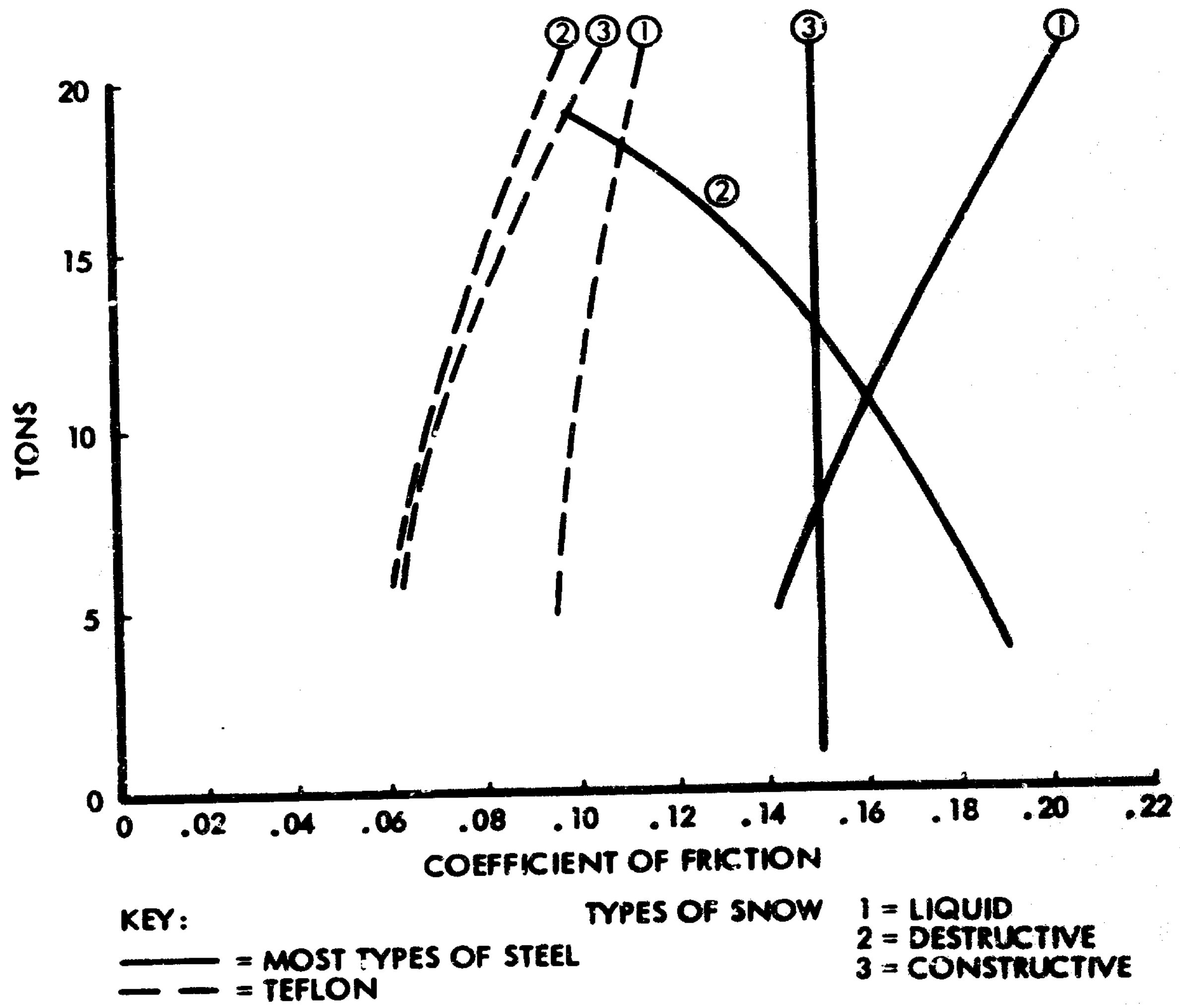
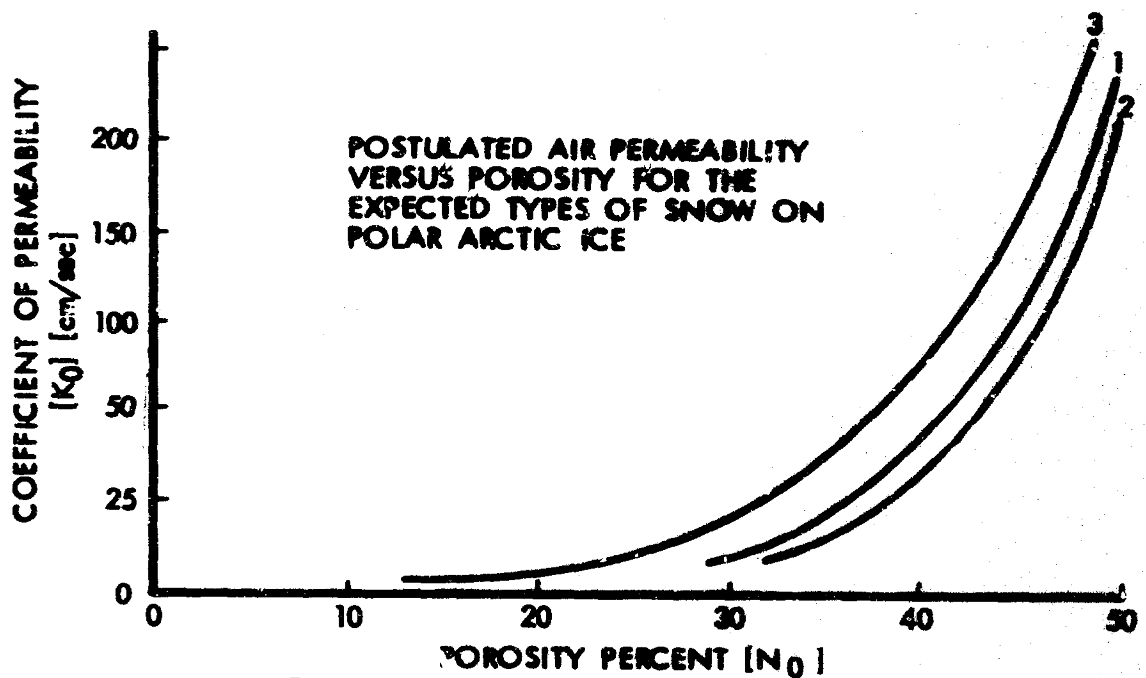


Figure 5-17: COEFFICIENTS OF KINETIC FRICTION



AFTER WATERHOUSE, NAKAYA AND OTHER

THE DIFFERENT TYPES OF SNOW AGE AT DIFFERENT RATES THUS LEADING TO VARIATION OF AVERAGE POROSITY OF THE SNOW COVER. THESE CURVES GIVE A WORKING ESTIMATION.

Figure 5-18: POSTULATED AIR PERMEABILITY vs POROSITY

5.3.7.1 Basic Geomorphic Snow Types

FLAT SURFACE TYPES (Figure 5-19)

Case A---Case A is a slow aging snow profile developing under a moderate winter climate. The ice surface is more or less continuous and is not excessively permeable. This snow is of only moderate strength unless the temperature conditions become quite low (-40°C) for extended time periods. If the snow exists through more than one season it increases in strength and unconfined compression, and shear values then raise.

Case B---The Case B snow profile is highly dependent on temperature fluctuations and included particulate matter. If sufficient ice lensing exists the snow will be strong, mechanically acting as a series of beams. The amount of constructive snow on the bottom need not degrade the strength properties of the entire profile so long as ice bands and lenses are significant. By the end of a winter season this type of profile is very strong and offers an excellent traffic surface.

Case C---This profile is a solid mass of liquid snow deposited on a flat ice surface. The ice is relatively impermeable. It is most common after an early winter snowstorm after which the temperature has dropped. This snow is usually quite rough on the surface, but as in Case B with ice lensing the material is quite strong with good unconfined compression and tensile characteristics. By the end of the season it also has strong shear characteristics.

Case D---The Case D type is one of the most deceptive from a mechanical properties standpoint. Either the material is blown in or deposited as a relatively dry snow. A hard crust then forms, under which a constructive metamorphic profile develops. The result is an apparent strong profile, but only because of the crust. The snow below is very weak and normally quite dry. The snow can be quite deep, but this is also misleading.

Case E---The Case E snow profile is the classic one usually pictured as sculptured snow. The profile is fairly strong and rough. The upper surface is relatively brittle, but the mass of the pack is definitely viscoelastic. It breaks down as large segments of beams. If drifting occurs against ice ridges it accentuates the relief and can thus overstate the ridging. Due to the strength of the sculptured surface, it is difficult for surveillance instrumentation to differentiate between ice and snow. The original snow deposit is usually formed in late fall or during winter, but the surface wind action carries out the geomorphic work. The snow maintains itself over extended time periods even in relatively warm weather.

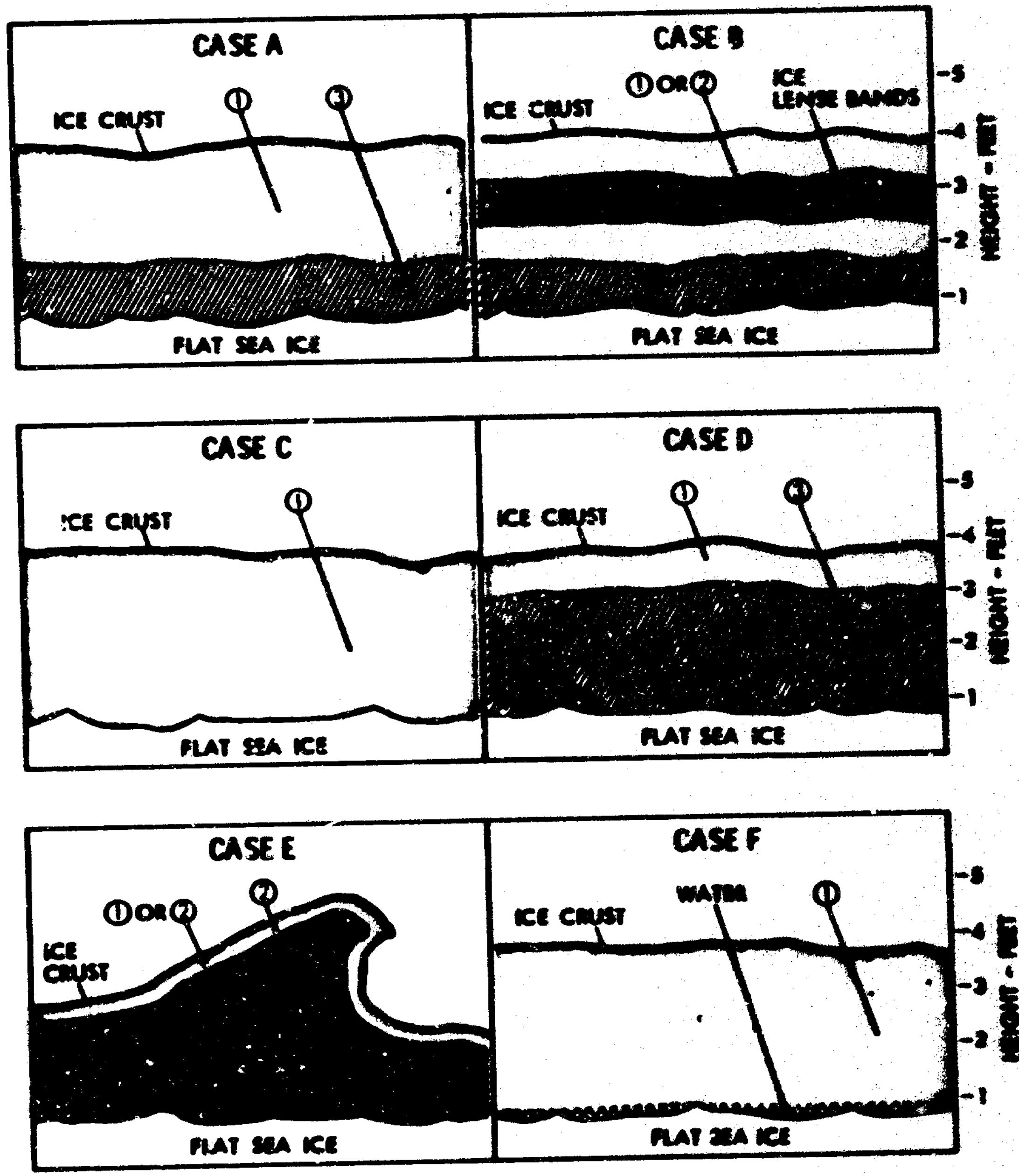


Figure 5-19: FLAT SURFACE SNOW TYPES

Case F---Case F is one of the ideal structural snow profile types. The bottom of the pack can be wet or dry, and the crust is soft. The pack itself is relatively strong if aged through a winter. It is a common type on the edge of the permanent polar pack. This snow profile is very temperature sensitive. If the temperatures becomes low, a very strong surface is developed although it appears porous. In warm weather, the material slowly degrades and becomes mushy in mid or late spring. It is not excessively layered and thus the mechanical properties are not those of beams. On an average the mechanical properties are midway between the weakest Type 2 and the strongest Type 1.

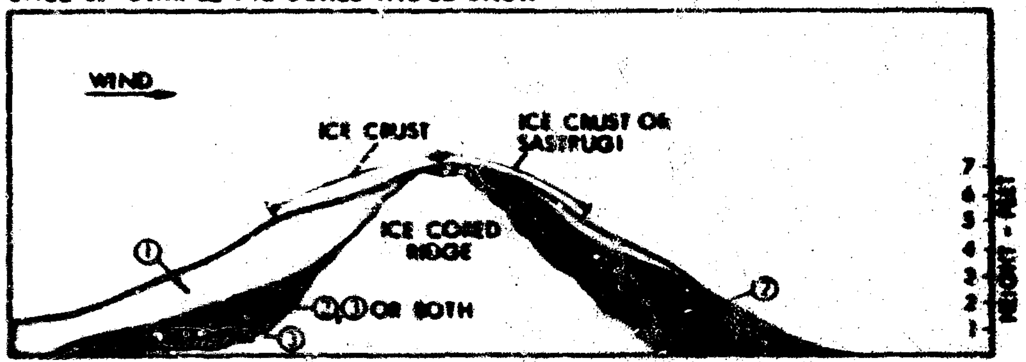
RIDGE TYPES (Figure 5-20)

Case G: Snow Upon Simple Ice Cored Ridge---A cored ridge can have a complex mantle of snow consisting of the three basic types. The driving force to produce such a pattern is a moderate to strong surface wind, a moderate to quite moist atmosphere above the ice surface, and diurnal or storm-engendered cycling of the ambient snow and air temperature. In this situation the foreslope of the ice ridge has a moderately strong snow mantle. The surface (Type 1) portion can vary considerably in strength depending on the amount of moisture supplied during mature stages of metamorphism. If well aged, it provides a strong ramp to the top of the ice ridge, and reaction strength under bending is increased by ice banding in the area below.

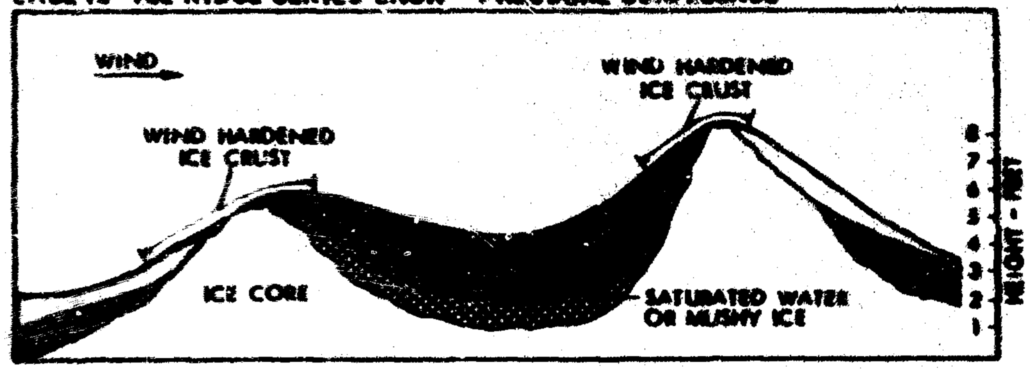
If aging has not taken place, the material is only moderately strong, sometimes even weak. The key is to properly interpret the meteorological history. The backside is of generally moderate to strong strength.

Case H: Snow Upon a Series of Ice Ridges in a Pressure Confluence---A series of moderately high ridges offers a site for this case. On the foremost side of the ridge series, the snow profile is similar to the simple ridge, dependent in degree on the force and duration of the wind. The far most leeside is also similar to the simple ridge case. The most important zone is the intra-ridge area. Here, there is normally permeable ice and opportunity for liquid water to accumulate; the bottom of the profile is quite wet and, if ambient temperatures permit, saturated. The snow above is generally fine grained, with good intergranular bonding of old aged (metamorphosed) crystal clusters. Anisotropic arching of the snow layers is not pronounced, and the snow ages to a rather uniform mass. In spring these areas must be carefully assessed for capillary movement of water which, if great, leads to a decided lessening of the structural character of the snow pack. Generally in fall and winter these intrazone areas are strong.

CASE G: SIMPLE ICE CORED RIDGE SNOW



CASE H: ICE RIDGE SERIES SNOW - PRESSURE CONFLUENCE



CASE J: ICE RIDGE SNOW - STRONGLY FAULTED AGGLOMERATION

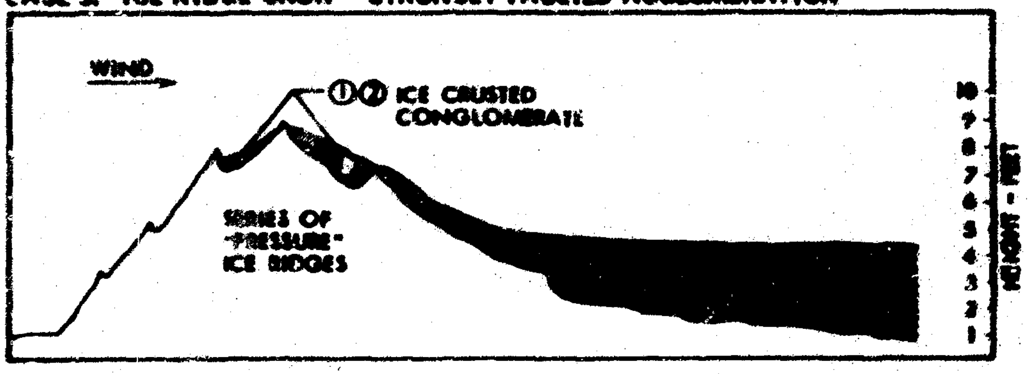
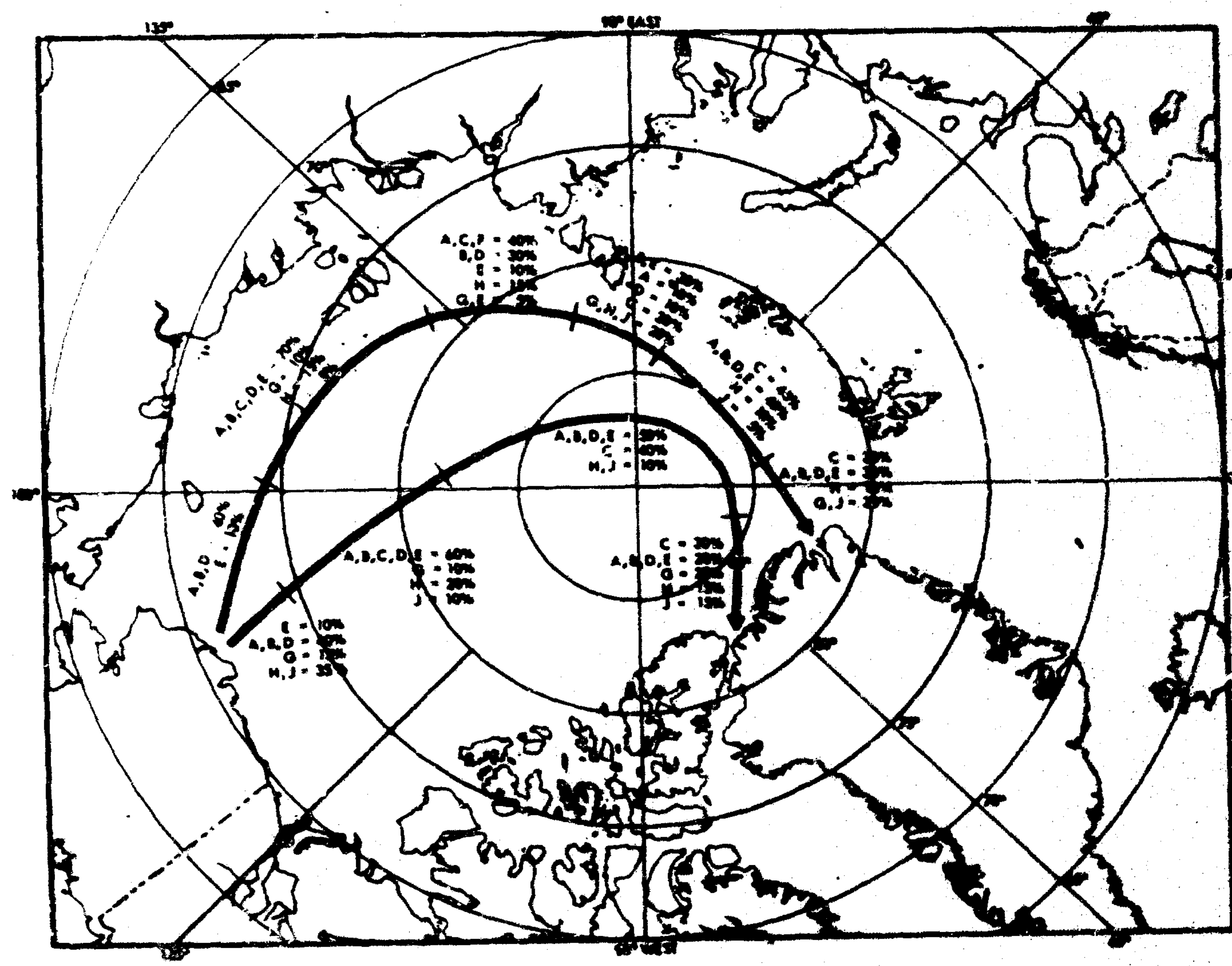


Figure 5-20: RIDGE SNOW TYPES



NOTE: OPEN WATER IS NOT CONSIDERED, PERCENTAGES ARE ON AN ASSUMED PERCENTAGE OF ACTUAL ICE IN AN AREA.

Figure 5-21: POSTULATED EXAMPLE OF EXPECTED SNOW TYPES AND PERCENTAGE OF AREA IN THE WINTER SEASON

Case J: Snow Upon a Strongly Faulted Agglomeration of Ice Ridges---As shown in Figure 5-20, the leeside of the ice ridge is the most important zone. On the foreslope most of the snow is swept clean due to either turbulence or the microclimate being nonbeneficial to the building of a strong material. The upper surface of the ridges is an agglomeration of liquid, destructive snow types and ice globules or crusts. The leeside of the ridge generally should have a mechanically hard destructive type of snow with banding and layering in the profile. Since the ice near this portion of the ridges is not permeable to a high degree, most of the liquid water flows downslope from the upper surface of the pressure ridges. The amount of liquid water available determines the roughness and amount of surface ice. Further away from the ridge line it is possible to build a series of "mush" or liquid water pools with thin skins of snow or ice. These pools will develop if the structure is such that it has a small void ratio and an appreciable amount of entrained dirt or rock. Generally such areas are strong and offer good trafficability.

5.3.7.2 Example Geomorphic Snow Profile Across the Arctic Basin

The map of Figure 5-21 shows two generalized transects across the basin during the winter season. It should be noted that the snow conditions shown are postulated and could easily be altered with the addition of new field data.

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5.5 ICE AND SNOW GLOSSARY

Ablation — The disappearance of snow and ice from a pack or sheet by melting and/or evaporation.

Age-Hardening — The natural physical processes involving temperature and pressure changes by which an ice or snow cover becomes physically stronger with the passage of time.

Dry Snow — A snow with little or no "free" liquid water associated with the snowflakes and snow crystals. In such a snow pack, the film of water around the grains is confined to ionicly bound water and there is very little liquid or vapor moisture in the intergranular space. Such snow grains are hard and dry, feeling to the touch as sand grains.

Geomorphic Nature — The surface configuration of snow, ice, or a ground surface (i.e., blowouts, ridges, trenches).

Hardness	The resistance to penetration by a rigid object into the snow or ice. The most common instrument used to measure hardness is a penetrometer.
Hoar	A dry snow, which is either a needle-shaped frost or coarse dry snow grains within the snow pack. The hoar is of very weak strength and is often stable when insulated with a snow pack.
Ice	The solid crystalline form of water. The quality of an ice is variable in crysta-line structure and mechanical and chemical properties, depending on kind of water, ambient temperature, and vapor pressure at time of initiation.
Young Ice	A brittle ice, frequently with a degree of transparency. Can bear light to medium loads.
Winter Ice	Ice forming during the first season's growth. Begins to change in color; aging increases its load-carrying ability.
Biannual Ice	Ice in the process of aging through a second winter, and taking on a blue coloration. It has had the opportunity to expel some salt if it is sea ice, and is able to carry considerable loads.
Polar Ice	The thickest, heaviest ice found in the polar basin. It is more than one season in age and is the strongest ice found in the basin.
Ice Island	A tabular iceberg whose extent may be measured in miles.
Ice Pack	Any type of areal configuration of floating ice which is closely driven together.
Intergranular Bonds	The physiochemical forces of attraction which hold together the snow and ice crystals and depend on the nature of the forces present.
Metamorphism	The change that takes place with time in structure and texture; it is initiated when the snowflake is formed, continues to the newly formed ice crystal and ends at the time melt or ablation destroys the original crystal. Metamorphism in snow in the Arctic Basin consists of three types: liquid, destructive, and constructive.

Sastrugi	The shaping (configuration) process and the resulting snow surface caused by wind erosion of the material.
Snow or Ice Aggregates	The composite mixture of snow and ice crystals of various forms, shapes sizes, and physical properties which makeup a snow pack or ice sheet.
Structure	The arrangement of the granular snow/ice aggrate and the associated liquid and gaseous components. Snow and ice as materials tend to be anisotropic.
Wet Snow	A snow that has a large volume of liquid water associated with the snow and ice crystals (of the snow pack), both as fluid films on the grains and as liquid in the void spaces. To the touch, such snow is slippery and often free water can be squeezed from it.

6.0 ARCTIC ICE PACK

6.1 INTRODUCTION

The ice pack that dominates the Arctic Ocean is perhaps the most critical environmental feature that affects the operation and mobility of both man and vehicles. This section gathers available information on the ice pack to provide both geographic and synoptic information of the more important characteristics of the pack.

Since exploration of the detail structure of the ice pack is in its infancy, many gaps and uncertainties exist in our knowledge. This is not too surprising because only in recent years has the importance of this area for military and commercial operations been recognized. Flights of aircraft over the arctic are common, yet landings on the pack have been relatively infrequent. Movement of ships around the ice pack and, in some cases penetration into the pack, has gone on for several centuries, but in general the pack ice has represented a formidable barrier. The advent of the nuclear submarine has permitted a new mode of pack penetration from below and has opened a new capability of making studies of the pack bottom as well as the sea floor beneath the pack. Long traverses on the top surface of the pack have been restricted to dogsleds.

Studies conducted in the arctic have been largely scientific. Although helpful, they do not provide the synoptic and statistical information of the type necessary for evaluation of system operation. This section is based largely on the surveys of the Naval Oceanographic Office and includes information derived from submarine data and many miscellaneous sources.

6.2 DATA SOURCES

6.2.1 Birds Eye Observations

The only extensive synoptic and geopgrahic coverage of the arctic ice pack is provided by Project Birds Eye, conducted by the U. S. Naval Oceanographic Office. The flights were initiated in March 1962, and have been conducted since that time. Planned objectives of the flights may vary somewhat, but each flight has the following objectives generally applicable to this study:

"1. Collection of ice and related environmental data for the following purposes:

(a) Accumulate a statistical body of data sufficient to define the geographical and seasonal distribution of critical variables.

(b) Provide periodic sampling which can be related to meteorological and oceanographic conditions by hindcasting.

2. Aerial photography of ice features.

3. Evaluation of airborne radar imagery." (Reference 1)

Since the method of observation utilized is pertinent to the type of data obtained and to the reliability that can be placed on the data, it is desirable to briefly review the procedures used.

Each aircraft carries three ice observers who log particular ice characteristics by means of visual observation. One observer logs information on the number and size of water openings, a second logs information of ice ridging, and the third logs ice data suitable for encoding in World Meteorological Organization (WMO) format. The observations of the latter are taken every 5 or 10 minutes and constitute spot observations encompassing a semicircular area ahead of the aircraft with a radius of 2 nautical miles. This observer estimates ice types, topography, water openings, and other characteristics in terms of the areal coverage of each feature. The other observers log data on a continuous basis during the intervals between the WMO spots. The observation sequence is shown in Figure 6-1 (Reference 2).

The primary data source for this report was the WMO spot observation reports because these are the most comprehensive. In several areas and during certain seasons the number of observations was too small to be trustworthy; however, this data has been included because it often represents the only available information. In addition a random sampling by season was made from the reports of the water openings.

The most serious limitation of the Birds Eye data is the dependence on visual observation, which is highly subject to personal interpretation of the individual observer and to observation conditions. Another limitation arises from the published data, which is a transcription of a portion of the data contained in the flight logs. Pertinent data such as ridge height, for example, has been omitted. Despite the limitations of the Birds Eye data and the reservations that must be made regarding its validity, this data has been processed and reported as given.

6.2.2 Submarine Observations

Submarine data was obtained from a contracted under-ice communications study. This information covers the cruises of the U.S.S. Sargo and U.S.S. Seadragon during the summer and winter of 1960 and is thus quite limited. Nevertheless it does provide some geographic coverage not available

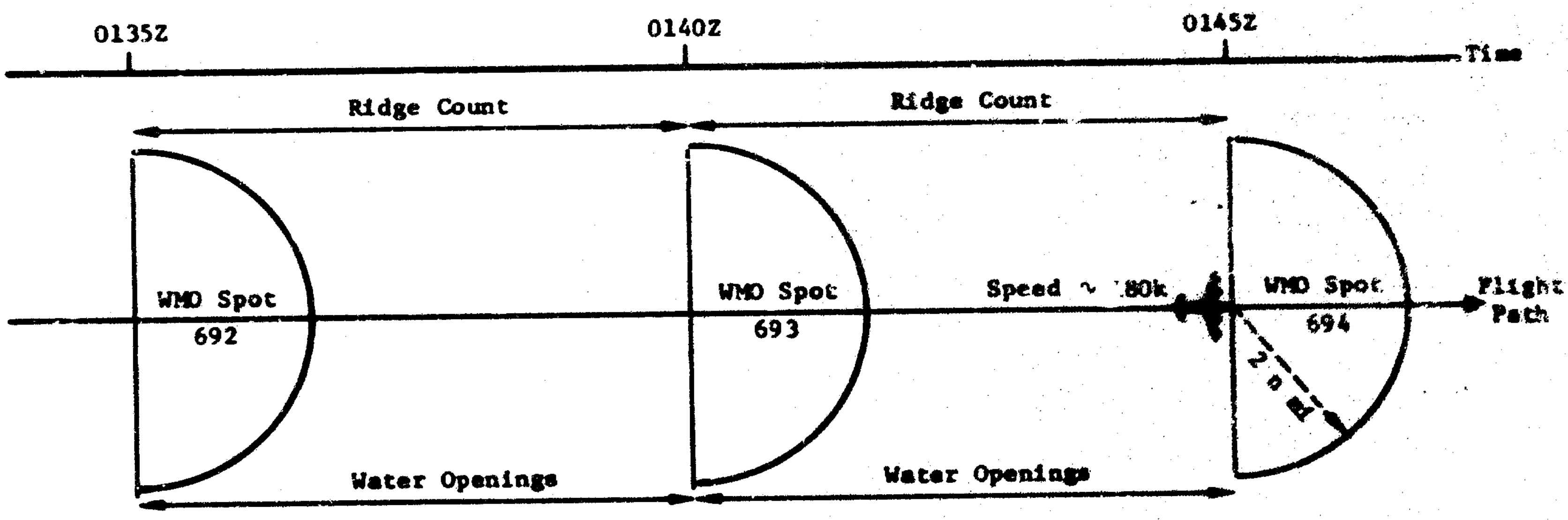


Figure 6-1: BIRDS EYE OBSERVATION PATTERN

from the Birds Eye flights, and also permits a crude but useful comparison with the Birds Eye coverage (Reference 3).

The submarine data, in contrast to the data from the Birds Eye WHO observer, is taken along a single track and hence gives no indication of areal extent of the features reported. It is believed that at this time, with the limited information available, it would be erroneous to attempt to convert this information to an area function that could be directly compared to the Birds Eye data.

6.2.3 Other Data

Some useful information, albeit highly limited in coverage, was provided by the Oceanographic Office in the form of aerial photography and laser altimeter records from several flight path segments aggregating about 3 miles in length in an area north of Barrow, Alaska. Unfortunately, this information was obtained during experimental flights and was subject to the usual problems encountered during such experiments. Necessary data, such as aircraft altitude, is lacking as is any correlation with reports from the observers. Infrared photographs were also made available which are highly interesting in that these showed many ice features not visible in ordinary light, but these also are too few in number and uncorrelated with other information to be of much significance (Reference 4).

For general data on the ice pack the best reference is the Oceanographic Atlas of the Polar Seas, Part II, Arctic (Reference 5).

6.3 ARRANGEMENT OF DATA

Because of the numerous variables and the complexity of each variable, presentation of ice data on seasonal charts is difficult if readability is of importance. Furthermore, the data herein utilized has been derived from two sources that are difficult to reconcile due to observational techniques. For these reasons the data is presented in the form of bar charts and tables independently for each source and include all pertinent ice information on a single page.

To replace seasonal charts covering the entire Arctic Basin, a sector system has been utilized with each ice data sheet keyed to a particular sector. Descriptions of the data given for each sector are contined in Section 6.5 along with additional information obtained from other sources.

6.4 SECTOR CHARTS

The variation of conditions that occur over the arctic pack are such that some distinctive regions are generally apparent; however, since these regions often do not conform to an easily defined

geographic grid system, utility dictated that a sector system be defined that would, insofar as possible, conform to known latitudes and longitudes. The entire arctic area was divided into sectors as shown in Figure 6-2. Where coastlines or islands provided obvious breaks, the sectors have been altered to follow these lines. Sectors are numbered systematically. The first letter indicates a ring centered on the pole, the number designates the quadrant beginning at 0° reading eastward, and the last letter designates the sector position in the quadrant, also reading eastward.

Figure 6-2 also shows the availability of Birds Eye and submarine data in each sector. Following the figure are data sheets for the sectors, arranged in alphabetical and numerical sequence. Where both Birds Eye and submarine data is available, the sheets are arranged sequentially.

Descriptions of the sector data are contained in Sections 6.5 through 6.5.6, along with additional information obtained from other sources.

6.5 ARCTIC ICE PACK CHARACTERISTICS

6.5.1 General Description

The major portion of the Arctic Ocean is covered throughout the year by heavy pack ice, which is usually impenetrable by surface ships. During late fall, winter, and spring and into the summer months many of the bordering seas and bays may likewise remain locked in ice and unnavigable by surface ships.

The ice that constitutes the polar ice pack is entirely sea ice, with the minor exception of the ice islands, which are broken portions of small ice shelves that occur along the north coasts of Ellesmere Island and Greenland. Large bergs of the type that occur along the Greenland coasts are not present in the pack.

The center of the "permanent" pack lies in the vicinity of 83°N and 160°W, almost 400 miles south of the pole. This displacement results both from the configuration of the Arctic Basin and from the warming effects of the northward-moving remnants of the North Atlantic Drift circulation through the Norwegian Sea and adjacent waters. The combination of the large water transport into the arctic from the Atlantic Ocean and the atmospheric wind patterns causes a complex circulation pattern to occur in the Arctic Ocean, which keeps the ice in continuous clockwise motion around the basin. This large motion is broken by many smaller circulatory motions in both the adjacent seas and in the Pacific portion of the arctic.

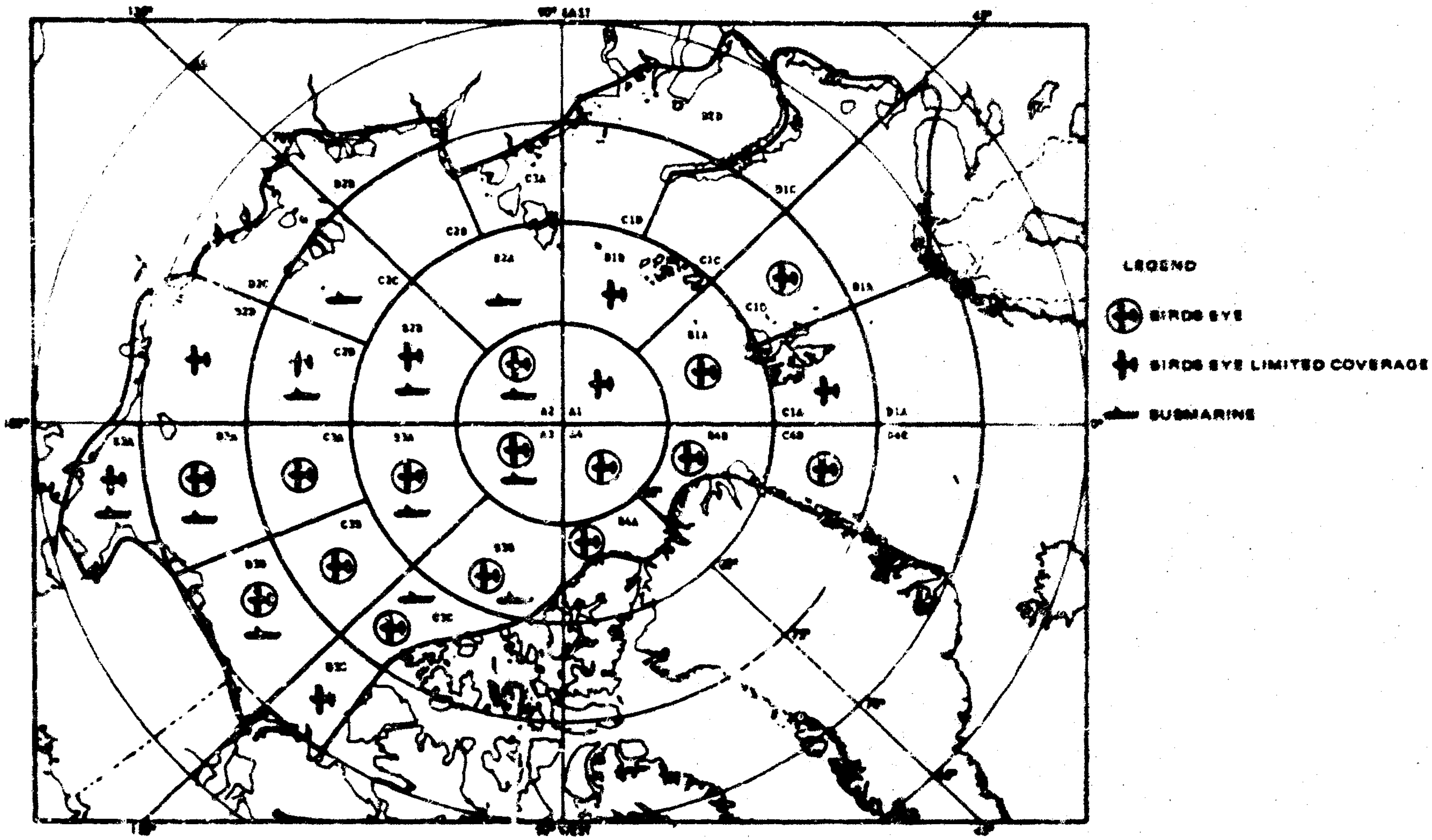
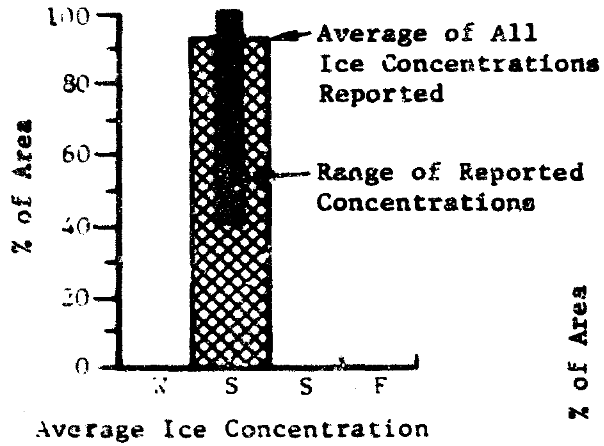
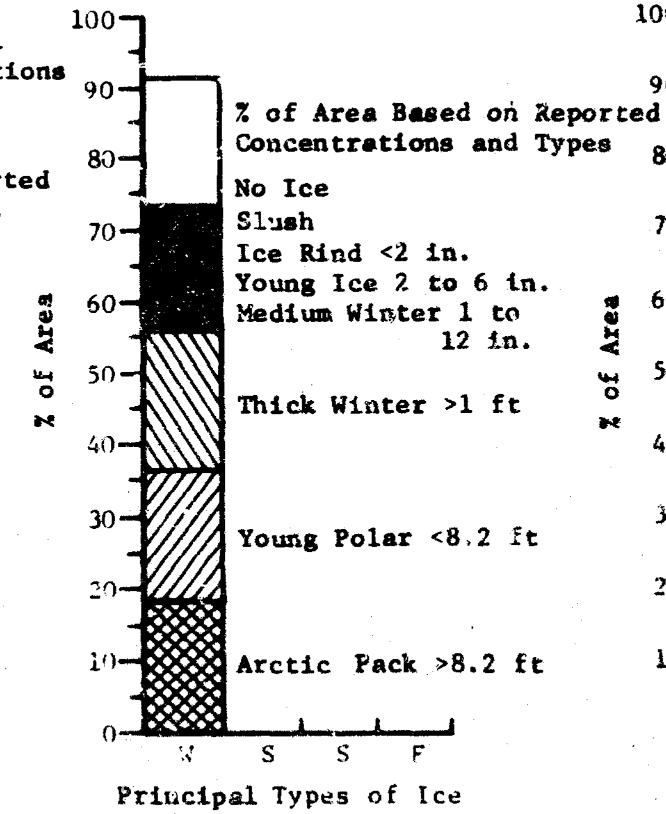
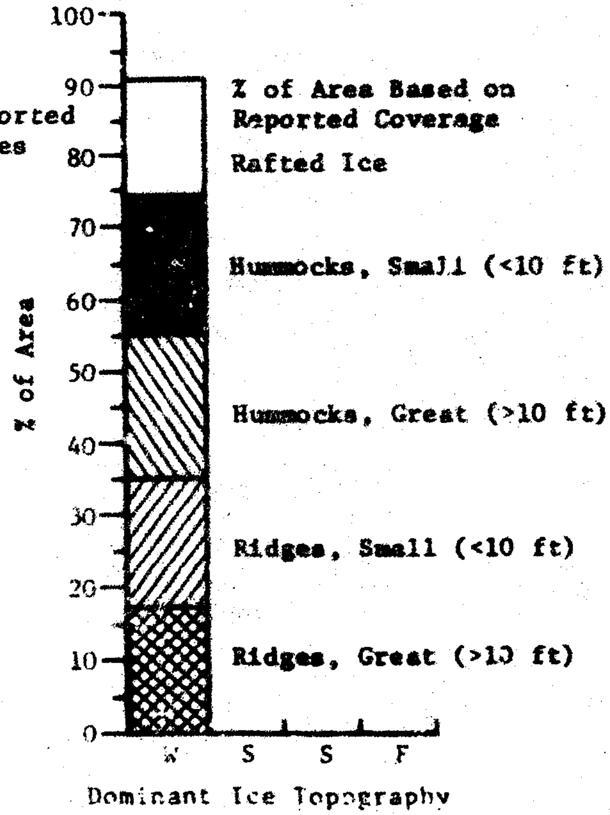
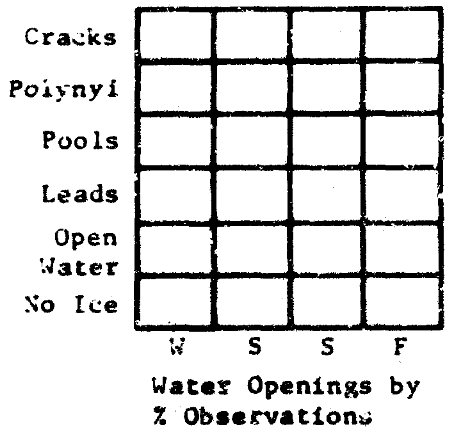


Figure 6-2: ICE CHARACTERISTICS SECTOR CHART









Data Source: Birds Eye

NUMBER OF OBSERVATIONS

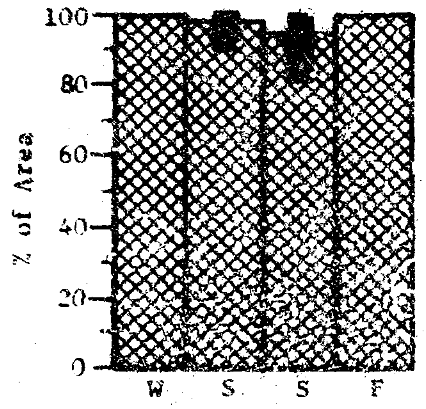
Winter
Spring
Summer
Fall

Number of observations utilized. Where data is too limited to be significant an * is utilized. This data is included for information only.

SECTOR DATA

Latitude
Longitude
Area (n mi^2)

Ice Characteristics
Sector KEY

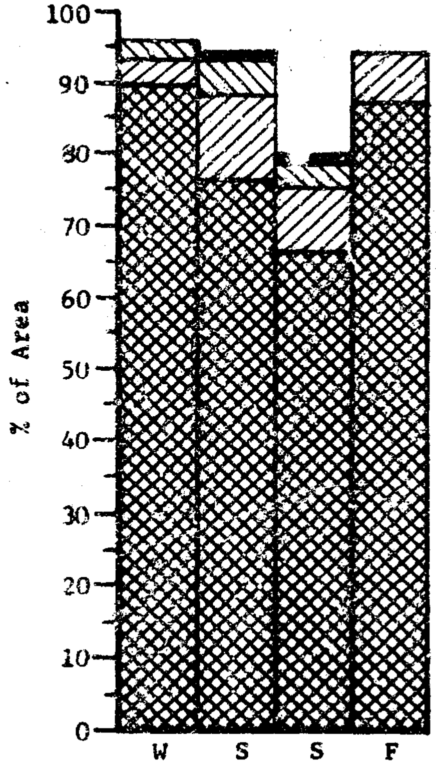


Average Ice Concentration

	W	S	S	F
Cracks	25	47	10	31
Polynyi		7		
Pools				
Leads	3	11		
Open Water		10	37	
No Ice				

Water Openings by % Observations

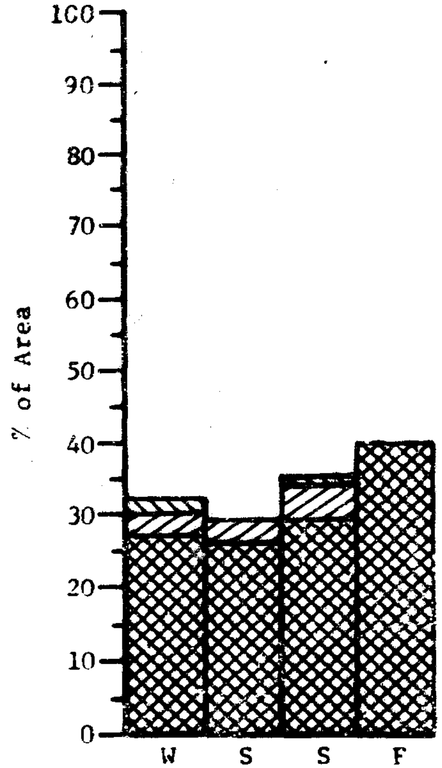
Data Source: Birds Eye



Principal Types of Ice

NUMBER OF OBSERVATIONS

Winter 36
Spring 90
Summer 49
Fall 19*



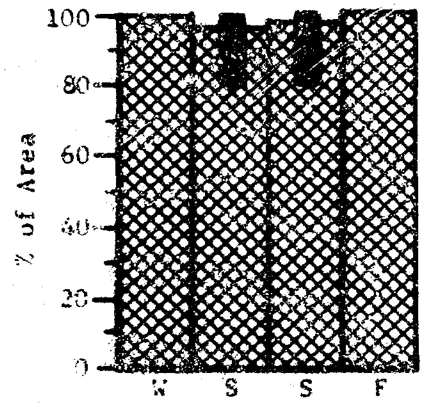
Dominant Ice Topography

SECTOR DATA

Latitude 85° - 90° N
Longitude 0° - 90° E
Area (n mi^2) 71,000

Ice Characteristics Sector A-1

*Data too limited to be significant

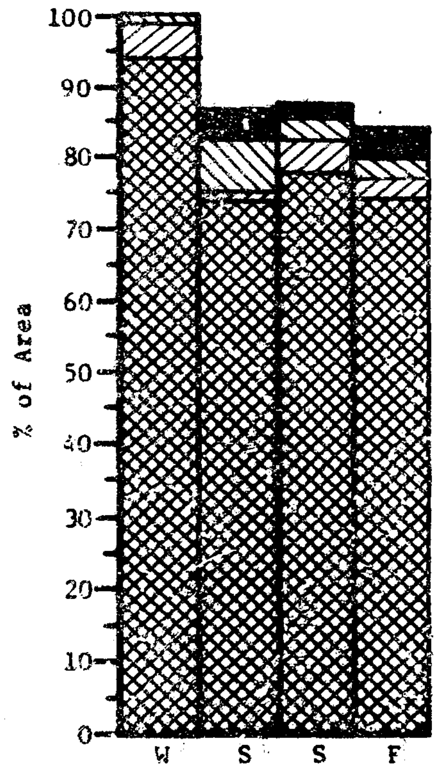


Average Ice Concentration

	W	S	S	F
Cracks	32	24	38	54
Polynyi				
Pools			1	2
Leads			22	
Open Water		26	13	
No Ice				

Water Openings by % Observations

Data Source: Birds Eye



Principal Types of Ice

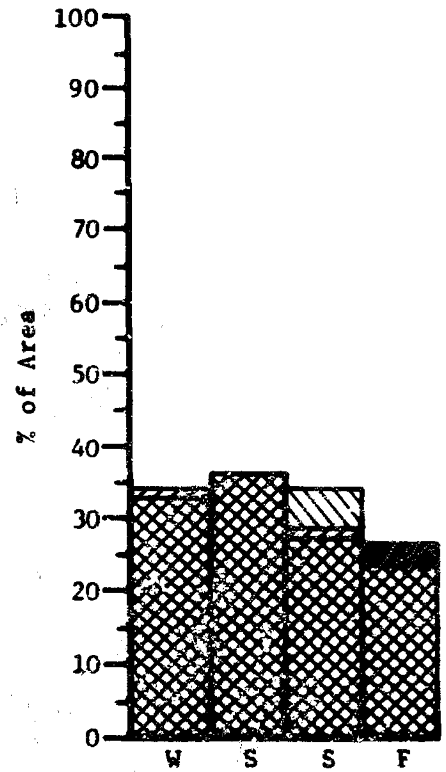
NUMBER OF OBSERVATIONS

Winter 41

Spring 41

Summer 11?

Fall 54



Dominant Ice Topography

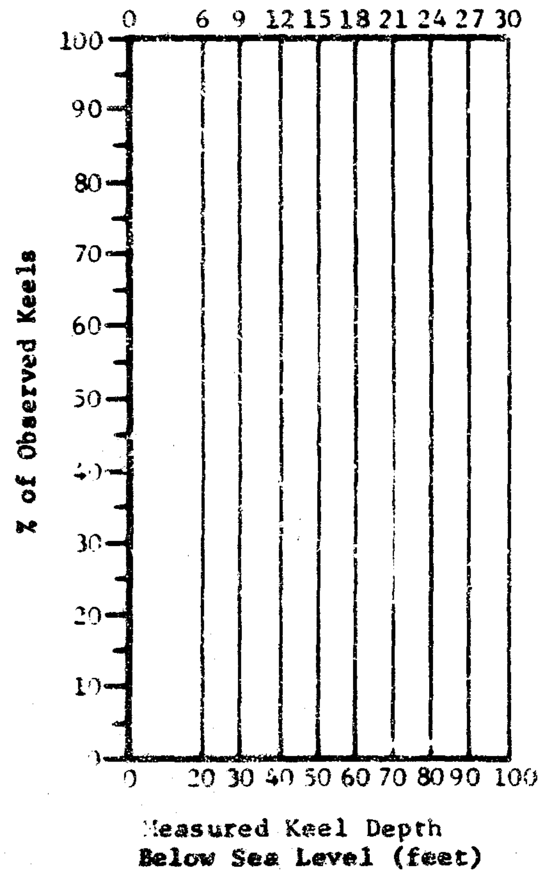
SECTOR DATA

Latitude 85° - 90°N

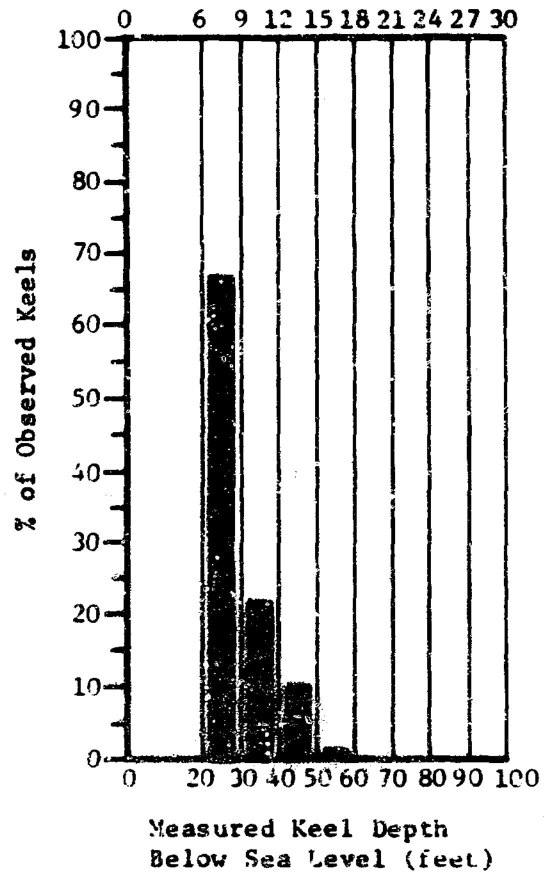
Longitude 90° - 180°E

Area (n mi^2) 71,000

Ice Characteristics
Sector A-2



WINTER



SUMMER

	W	S
Openings		7
Ice		93
Keels		10

% of Observed Track

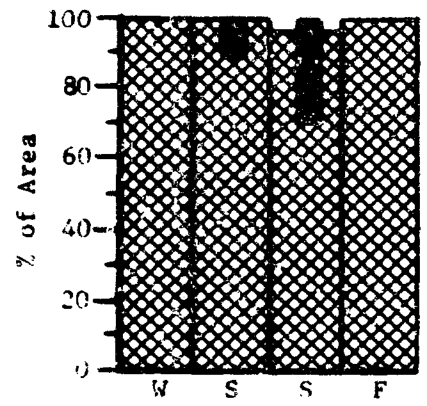
Observations	W	S
Track Segments	No	4
Total Length (n mi)	Data	17

SECTOR DATA

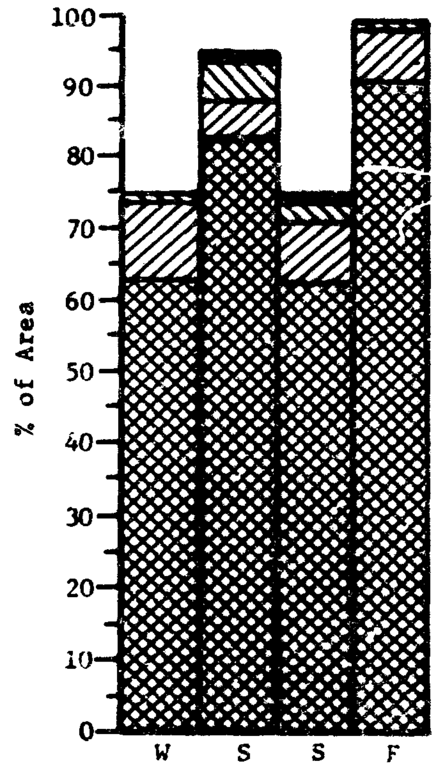
Latitude	85° - 90°N
Longitude	90° - 180°E
Area (n mi^2)	71,000

Ice Characteristics
Sector A-2

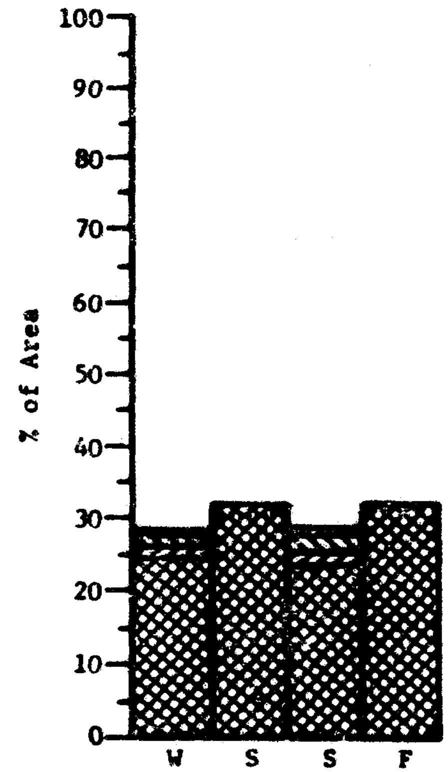
Data Source: USS Sargo and USS Seadragon 1960



Average Ice Concentration



Principal Types of Ice



Dominant Ice Topography

	W	S	S	F
Cracks	37	52	35	32
Polynyi				
Pools			21	
Leads		1	8	
Open Water		3	30	5
No Ice				

Water Openings by % Observations

Data Source: Birds Eye

NUMBER OF OBSERVATIONS

Winter	113
Spring	109
Summer	150
Fall	69

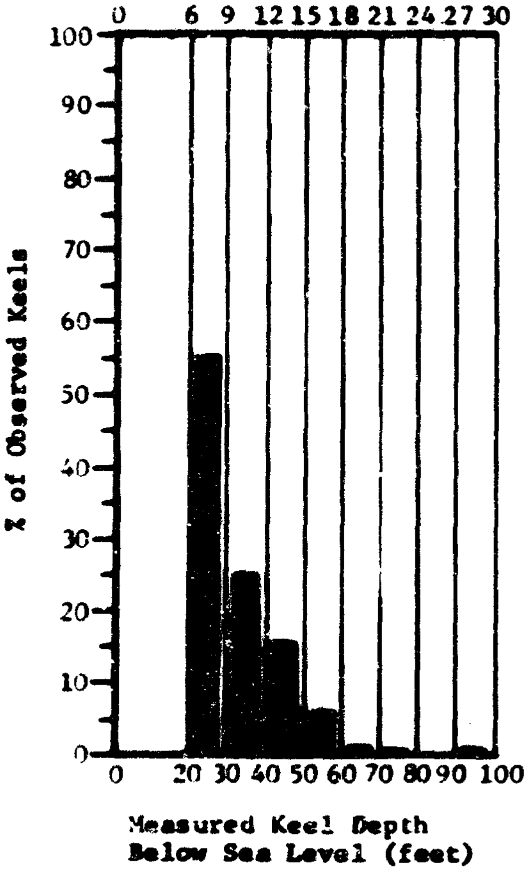
SECTOR DATA

Latitude 85° - 90°N

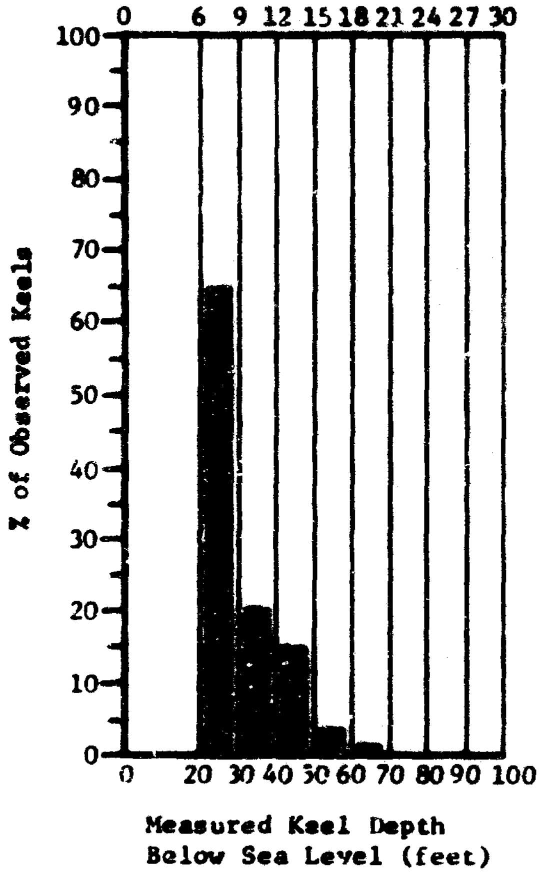
Longitude 180° - 90°W

Area (n mi^2) 71,000

Ice Characteristics
Sector A-3



WINTER



SUMMER

	W	S
Openings	1	5
Ice	99	95
Keels	15	15

% of Observed Track

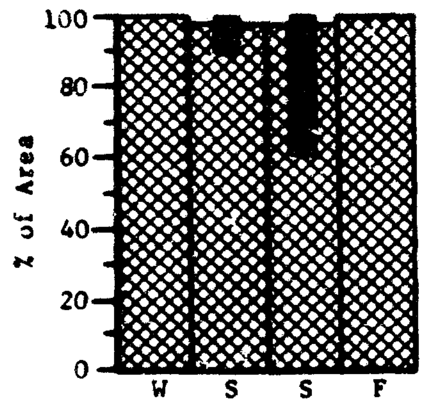
Observations	W	S
Track Segments	4	2
Total Length (n mi)	56	32

Data Source: USS Sargo and USS Seadragon 1960

SECTOR DATA

Latitude 85° - 90°N
Longitude 180° - 90°W
Area (n mi^2) 71,000

Ice Characteristics
Sector A-3

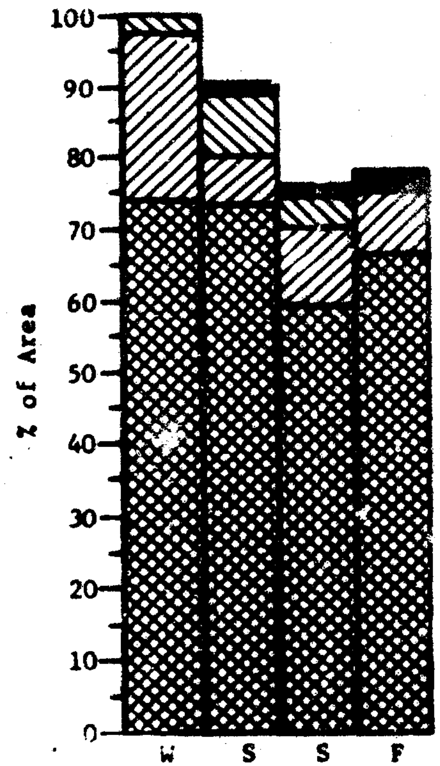


Average Ice Concentration

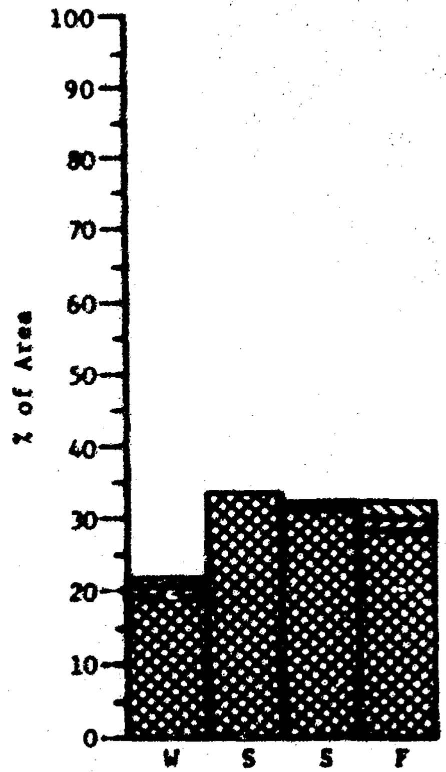
	W	S	S	F
Cracks	21	44	18	44
Polynyi		1		
Pools			3	
Leads		5	1	
Open Water		5	41	
No Ice				

Water Openings by % Observations

Data Source: Birds Eye



Principal Types of Ice



Dominant Ice Topography

NUMBER OF OBSERVATIONS

Winter	109
Spring	153
Summer	219
Fall	104

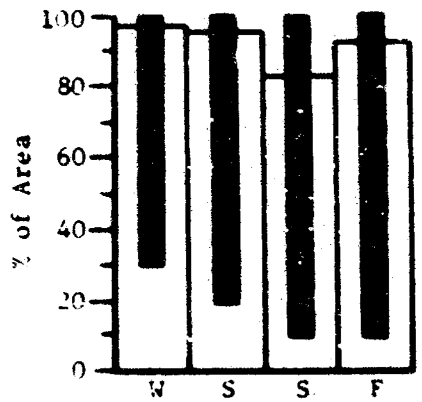
SECTOR DATA

Latitude 85° - 90°N

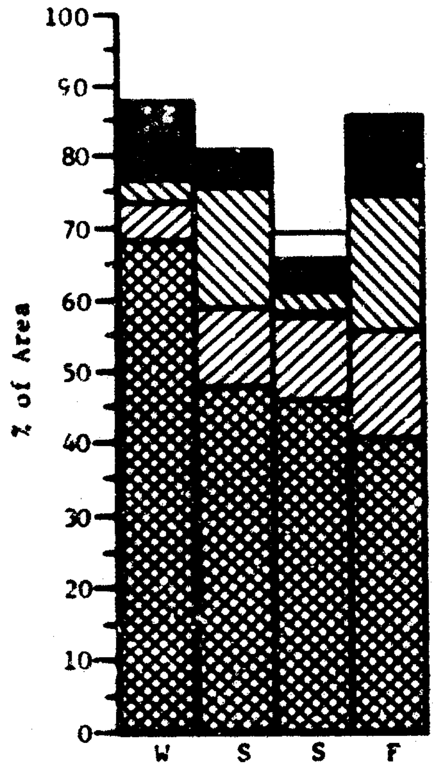
Longitude 90°W - 0°

Area (n mi²) 71,000

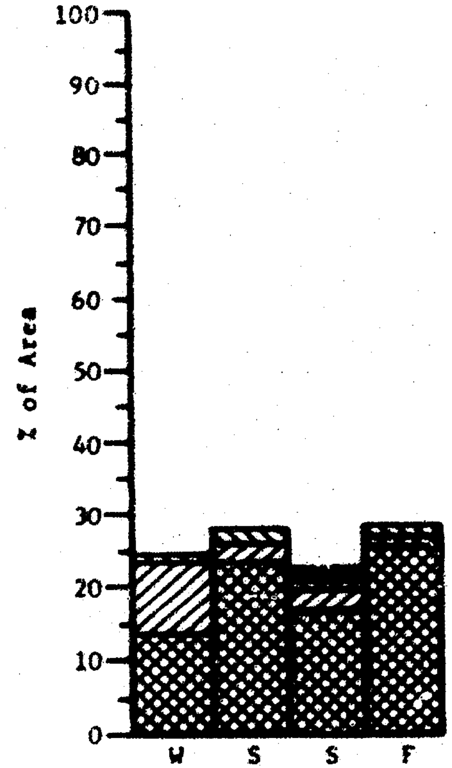
Ice Characteristics
Sector A-4



Average Ice Concentration



Principal Types of Ice



Dominant Ice Topography

	W	S	S	F
Cracks	21	30	15	38
Polynyi			2	
Pools				
Leads		3	1	
Open Water	6	25	41	24
No Ice			3	

Water Openings by % Observations

Data Source: Birds Eye

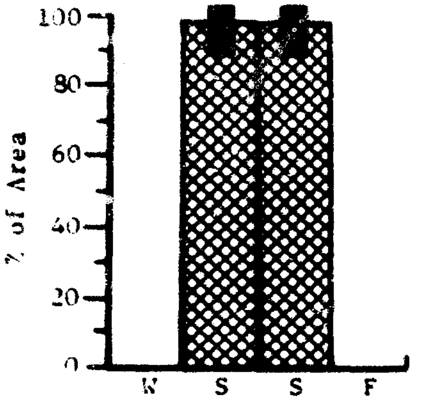
NUMBER OF OBSERVATIONS

Winter	68
Spring	140
Summer	162
Fall	108

SECTOR DATA

Latitude	80° - 85°N
Longitude	0° - 45°E
Area (n mi^2)	107,000

Ice Characteristics
Sector B-1A

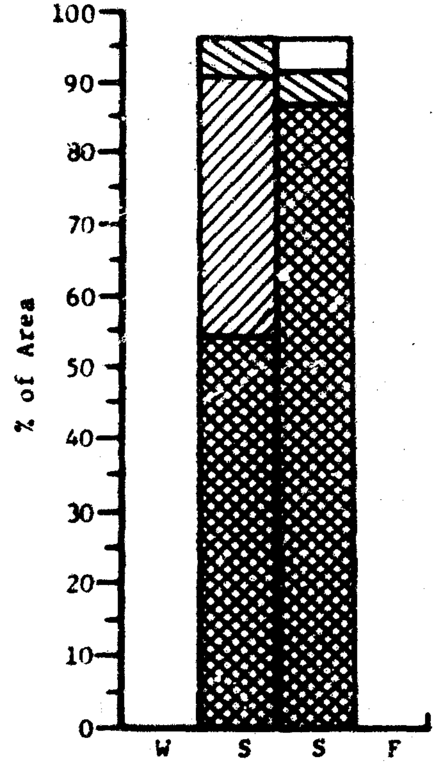


Average Ice Concentration

	W	S	S	F
Cracks		56	47	
Polynyi		6		
Pools				
Leads				
Open Water		6	26	
No Ice				

Water Openings by
% Observations

Data Source: Birds Eye



Principal Types of Ice

NUMBER OF OBSERVATIONS

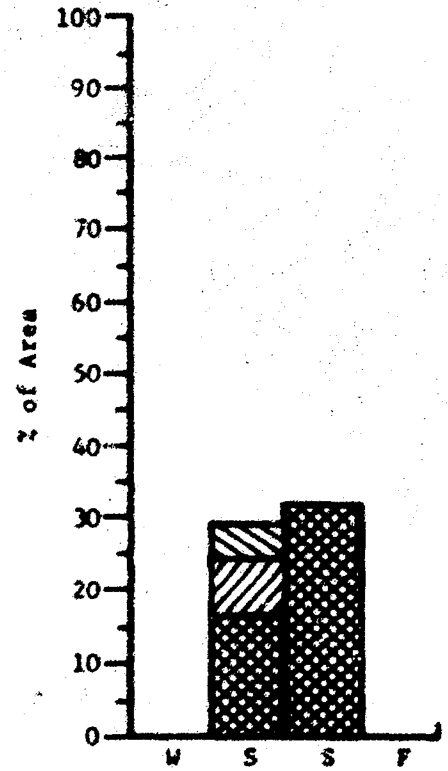
Winter No Data

Spring 16*

Summer 19*

Fall No Data

*Data too limited to be significant



Dominant Ice Topography

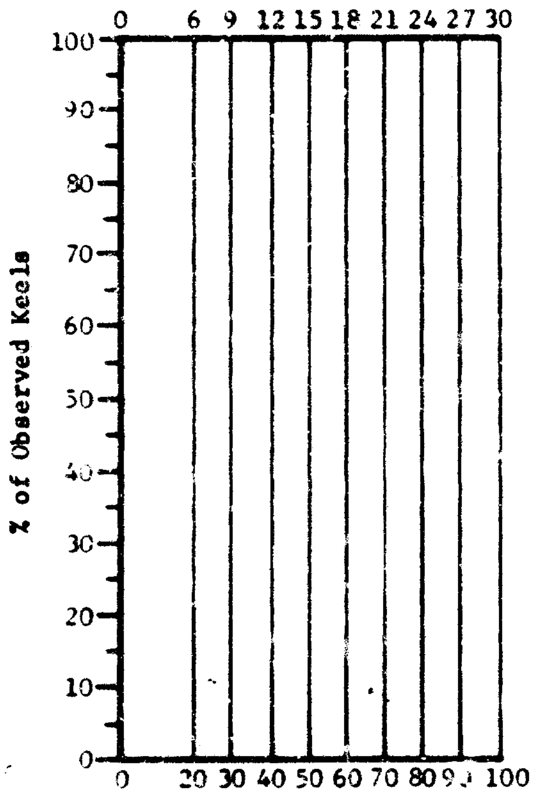
SECTOR DATA

Latitude 80° - 85°N

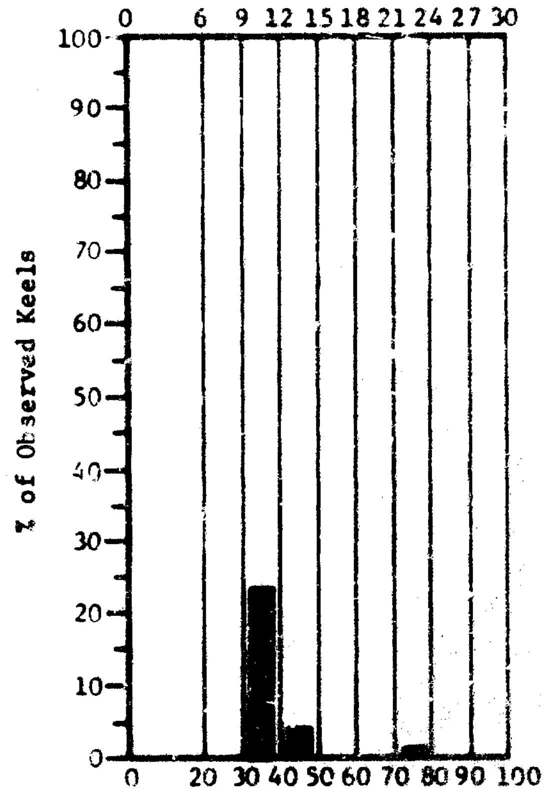
Longitude 45° - 90°E

Area (n mi^2) 10[illegible],000

Ice Characteristics
Sector B-1B



WINTER



SUMMER

	W	S
Openings		44
Ice		56
Keels		7

% of Observed Track

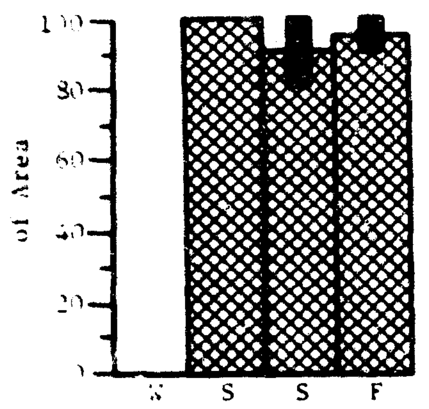
Observations	W	S
Track Segments	No	4
Total Length (n mi)	Data	50

Data Source: USS Sargo and USS Seadragon 1960

SECTOR DATA

Latitude	80° - 85°N
Longitude	90° -135°E
Area (n mi^2)	107,000

Ice Characteristics
Sector B-2A

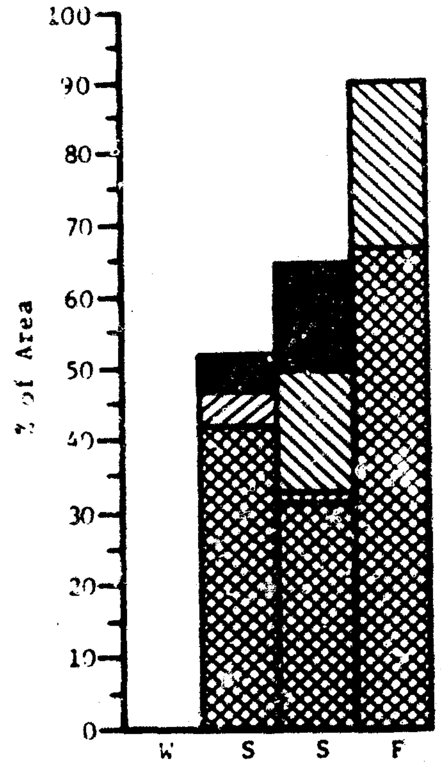


Average Ice Concentration

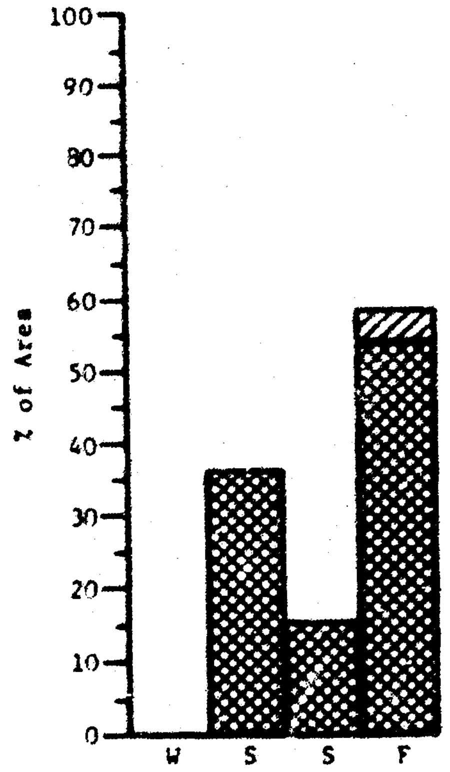
	W	S	S	F
Tracks		41	22	60
Polynyi				
Pools				
Leads		41		
Open Water			39	14
No Ice				

Water Openings by % Observations

Data Source: Birds Eye



Principal Types of Ice



Dominant Ice Topography

NUMBER OF OBSERVATIONS

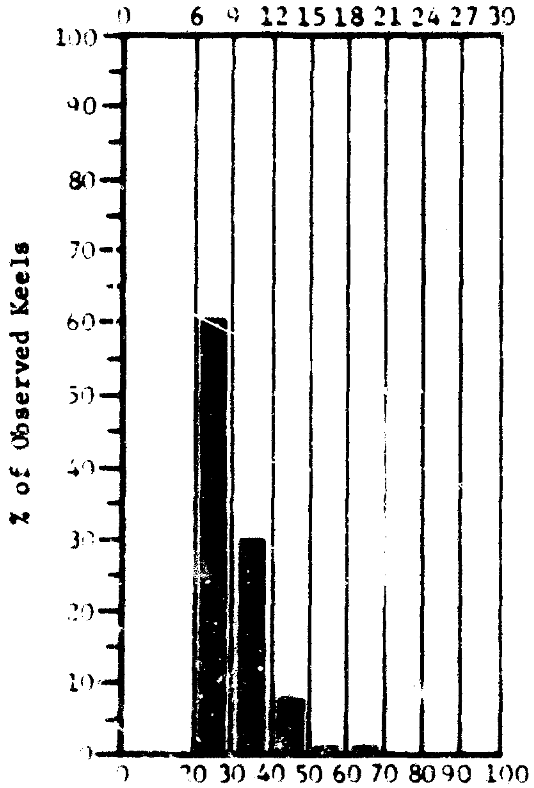
Winter	No Data
Spring	17*
Summer	18*
Fall	7*

SECTOR DATA

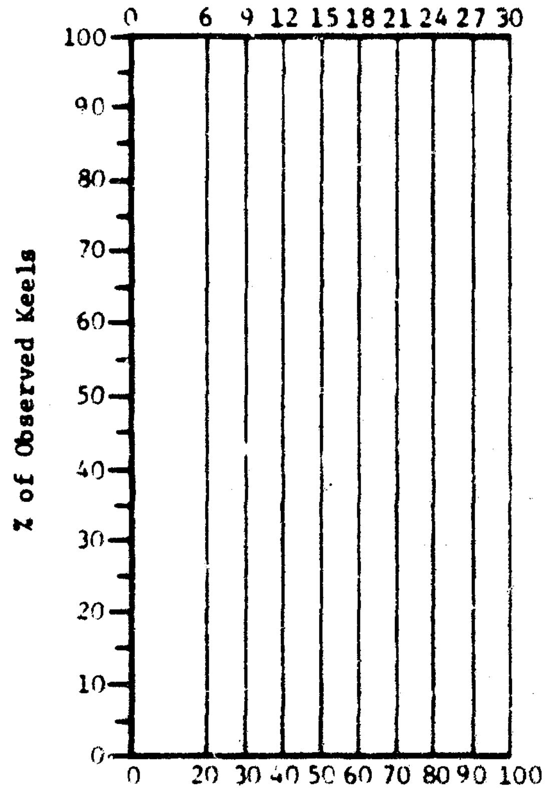
Latitude	80° - 85°N
Longitude	135°E - 180°
Area (n mi^2)	107,000

Ice Characteristics
Sector B-28

*Data too limited to be significant



WINTER



SUMMER

	W	S
Openings	5	
Ice	95	
Keels	23	

% of Observed Track

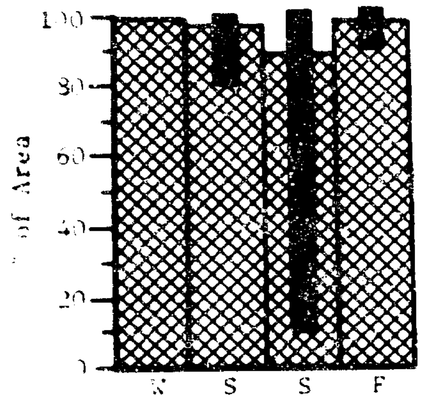
Observations	W	S
Track Segments	3	No
Total Length (n mi)	45	Data

Data Source: USS Sargo and USS Seadragon 1960

SECTOR DATA

Latitude 80° - 85°N
Longitude 135°E - 180°
Area (n mi^2) 107,000

Ice Characteristics
Sector B-28

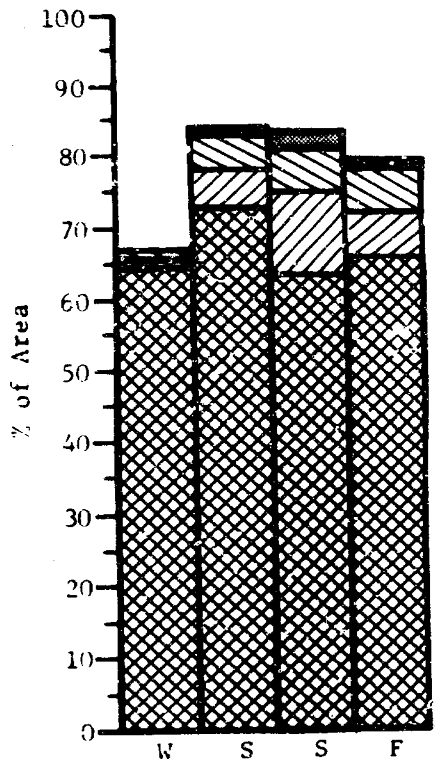


Average Ice Concentration

	W	S	S	F
Cracks	19	27	23	37
Polynyi			6	1
Pools				
Leads			1	
Open Water		1	42	3
No Ice				

Water Openings by % Observations

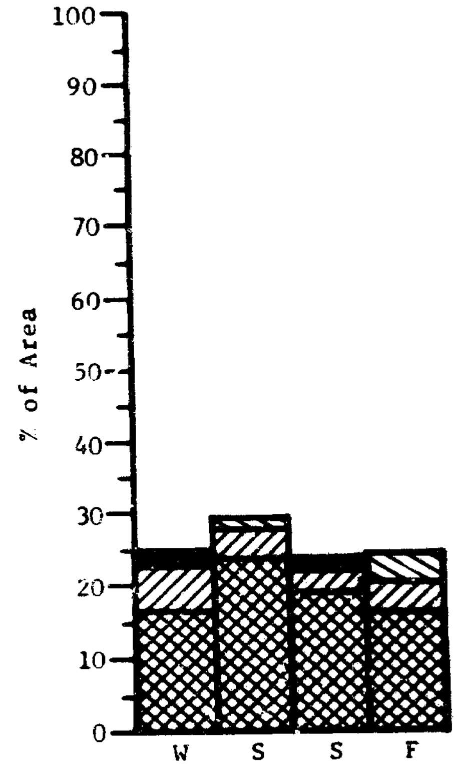
Data Source: Birds Eye



Principal Types of Ice

NUMBER OF OBSERVATIONS

Winter	108
Spring	135
Summer	242
Fall	117

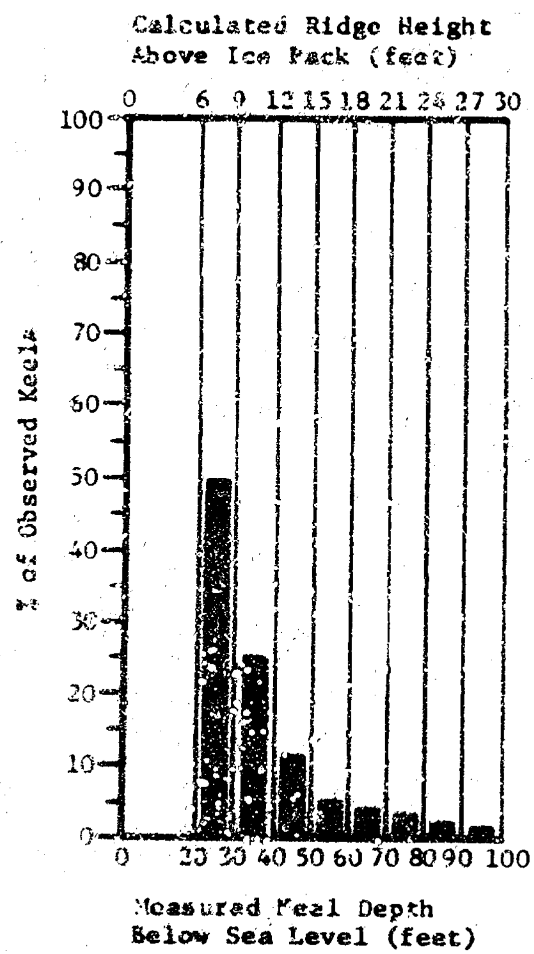


Dominant Ice Topography

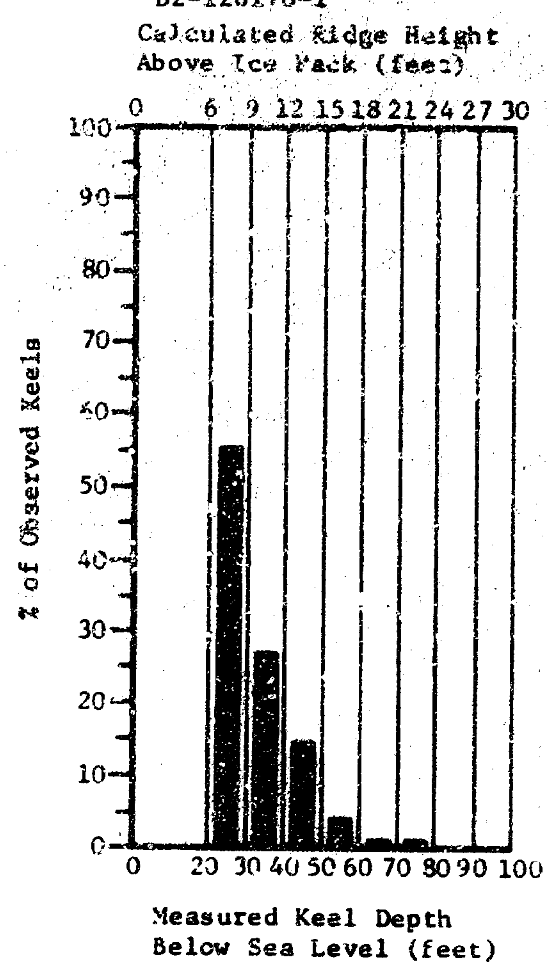
SECTOR DATA

Latitude	80° - 85°N
Longitude	180° - 135°W
Area (n mi^2)	107,300

Ice Characteristics
Sector B-3A



WINTER



SUMMER

	W	S
Openings	0	7
Ice	100	93
Keels	20	22

% of Observed Track

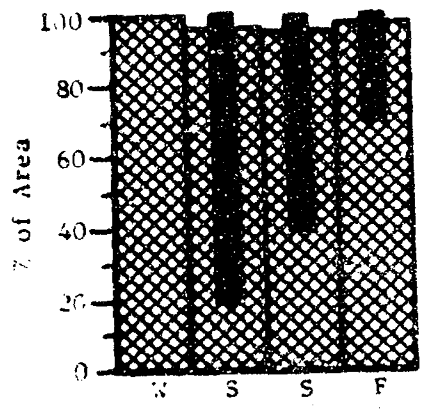
Observations	W	S
Track Segments	2	2
Total Length (n mi)	29	26

Data Source: USS Sargo and USS Seadragon 1960

SECTOR DATA

Latitude	80° - 85°N
Longitude	180° - 135°W
Area (n mi^2)	105,000

Ice Characteristics
Sector B-3A

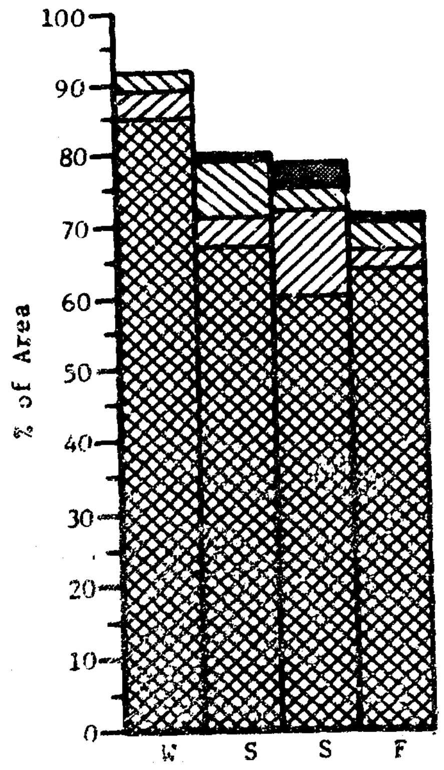


Average Ice Concentration

	W	S	S	F
Cracks	35	26	49	46
Polynyi				
Pools			1	
Leads		4	1	
Open Water	1	1	28	7
No Ice				

Water Openings by % Observations

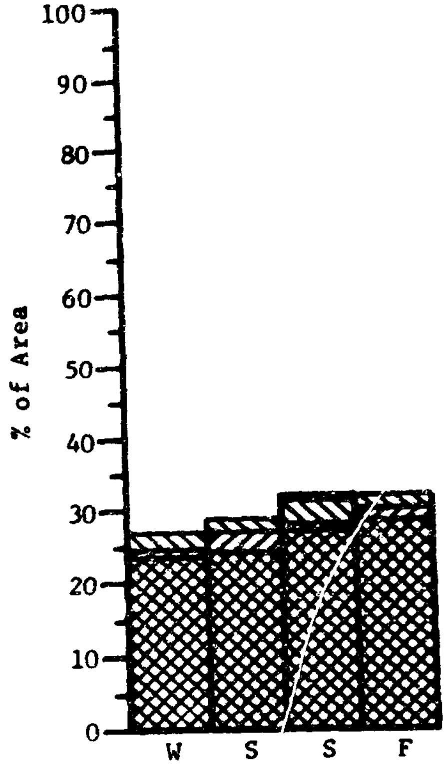
Data Source: Birds Eye



Principal Types of Ice

NUMBER OF OBSERVATIONS

Winter	205
Spring	184
Summer	288
Fall	176



Dominant Ice Topography

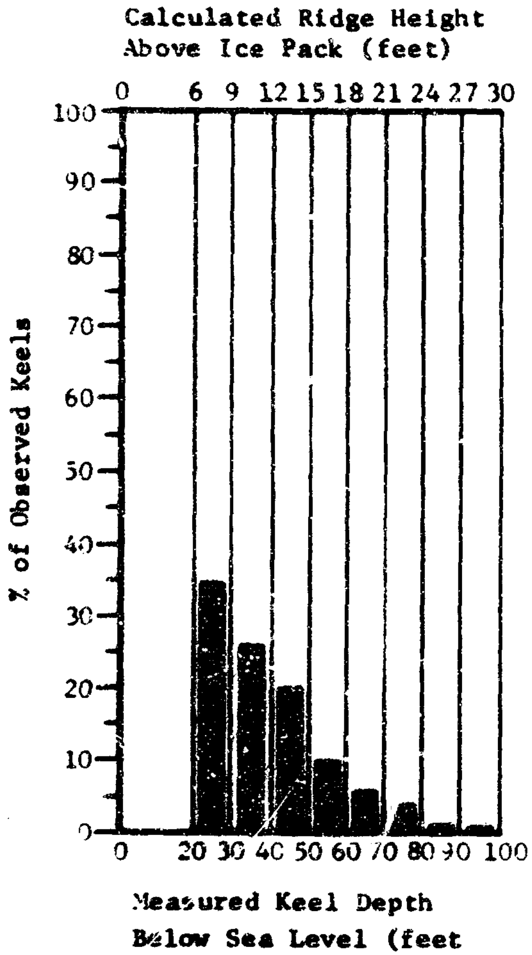
SECTOR DATA

Latitude 80° - 85°N

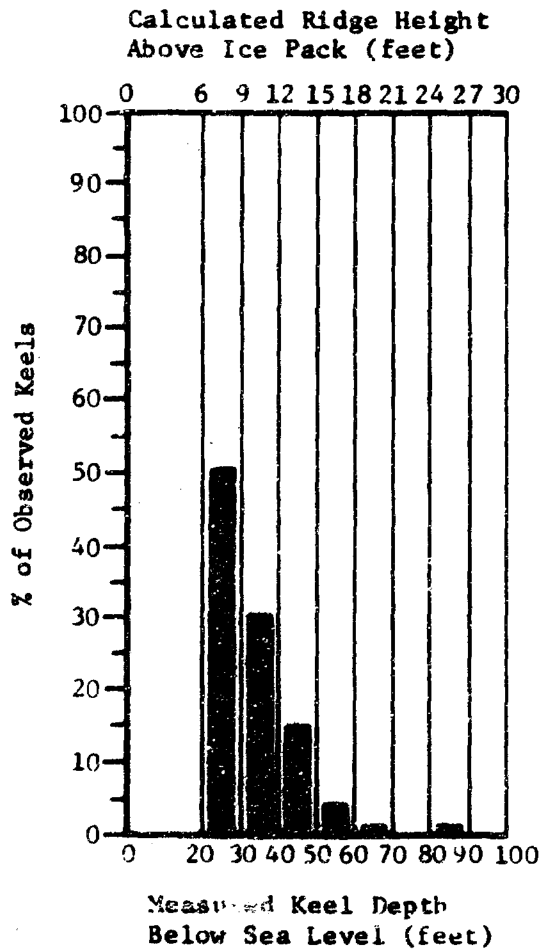
Longitude 135° - 90°W

Area (n mi^2) 105,000

Ice Characteristics
Sector B-3B



WINTER



SUMMER

	W	S
Openings	0	10
Ice	100	90
Keels	33	30

% of Observed Track

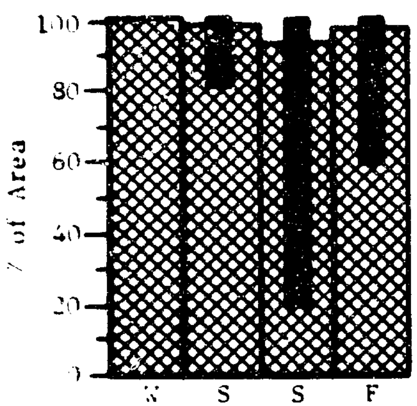
Observations	W	S
Track Segments	3	2
Total Length (n mi)	37	30

Data Source: USS Sargo and USS Seadragon 1960

SECTOR DATA

Latitude 80° - 85°N
Longitude 135° - 90°W
Area (n mi^2) 105,000

Ice Characteristics
Sector B3B

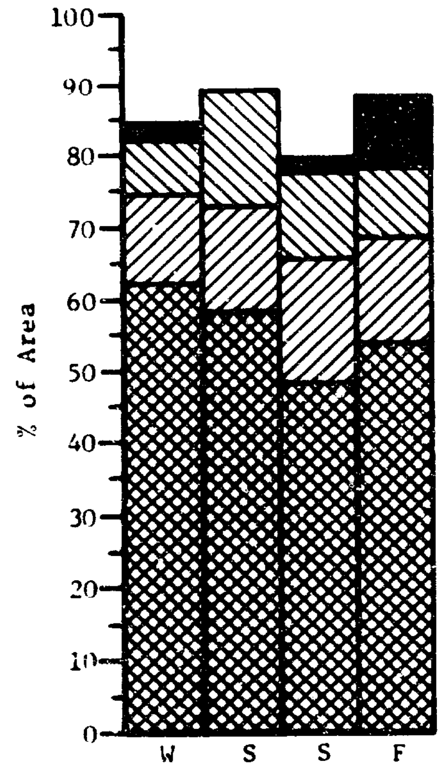


Average Ice Concentration

	W	S	S	F
Cracks	19	16	30	35
Polynyi		1	2	1
Pools			4	
Leads		1		
Open Water	1	11	40	11
No Ice				

Water Openings by
% Observations

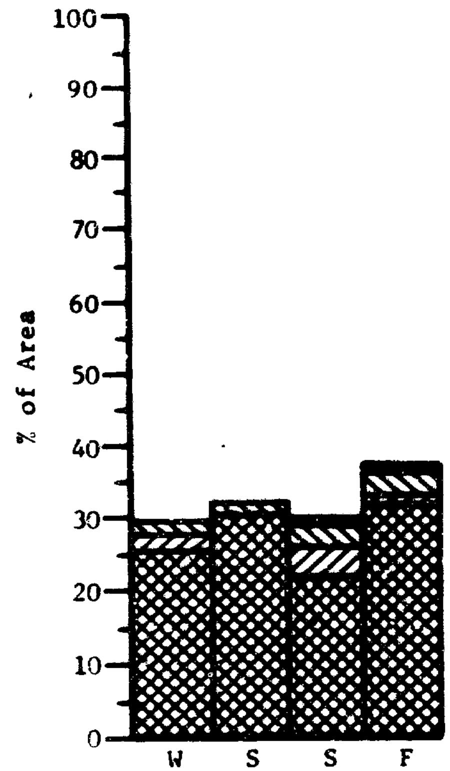
Data Source: Birds Eye



Principal Types of Ice

NUMBER OF OBSERVATIONS

Winter	174
Spring	169
Summer	272
Fall	198

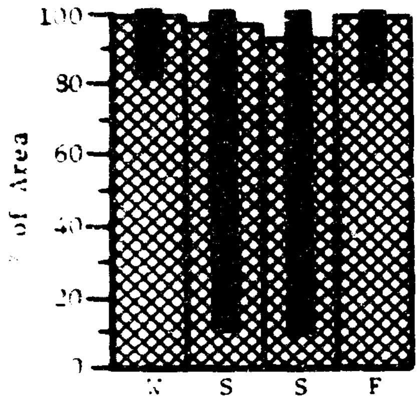


Dominant Ice Topography

SECTOR DATA

Latitude	80° - 85°N
Longitude	90° - 45°W
Area (n mi^2)	40,000

Ice Characteristics
Sector B-4A

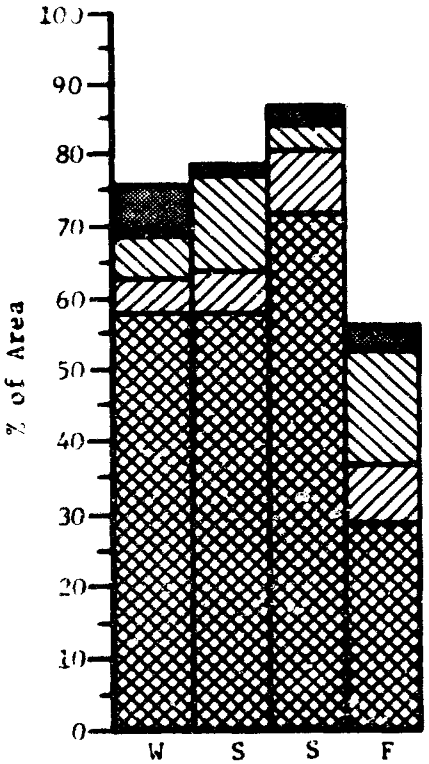


Average Ice Concentration

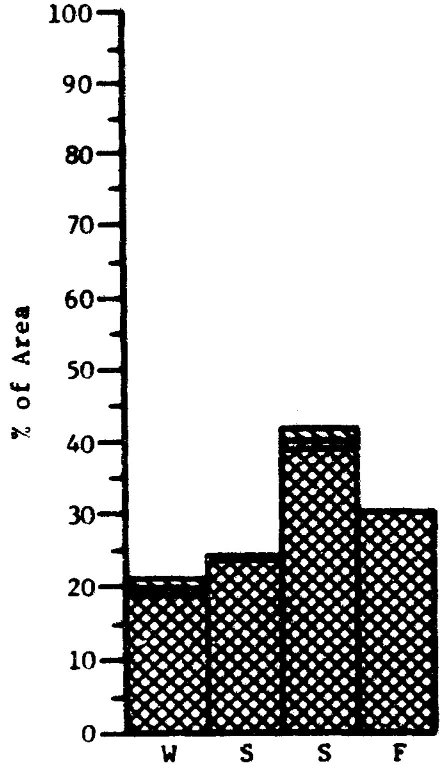
	W	S	S	F
Cracks	63	21	17	59
Polynyi		1	1	
Pools			6	
Leads		1	1	4
Open Water	9	21	52	22
No Ice				

Water Openings by
% Observations

Data Source: Birds Eye



Principal Types of Ice



Dominant Ice Topography

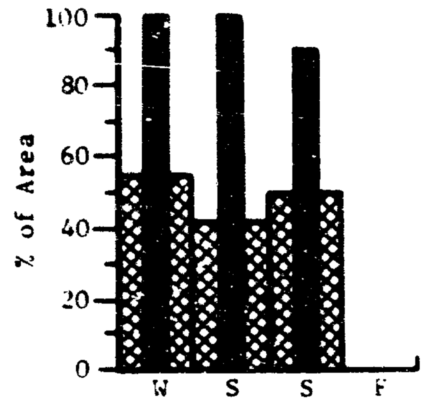
NUMBER OF OBSERVATIONS

Winter	67
Spring	122
Summer	174
Fall	69

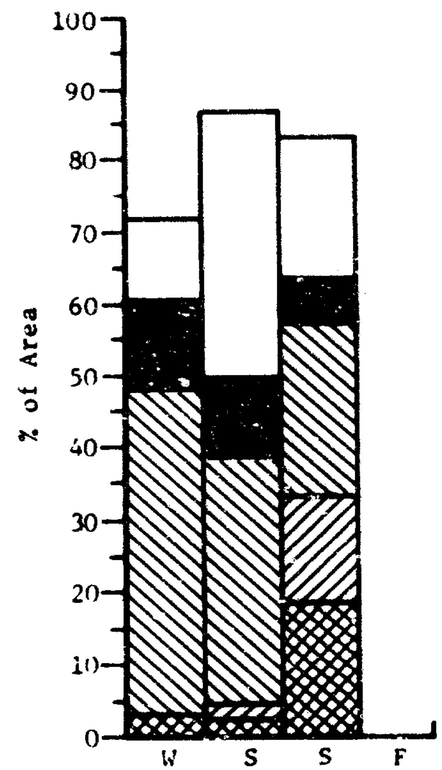
SECTOR DATA

Latitude	80° - 85°N
Longitude	45°W-0°
Area (n mi^2)	56,400

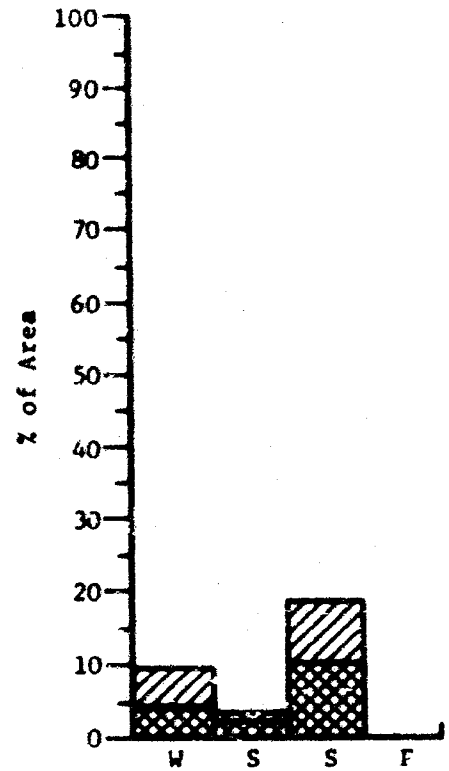
Ice Characteristics
Sector B-4B



Average Ice Concentration



Principal Types of Ice



Dominant Ice Topography

	W	S	S	F
Cracks	9			
Polynyi	2			
Pools	6			
Leads				
Open Water	69	63	58	
No Ice	11	37	17	

Water Openings by % Observations

Data Source: Birds Eye

NUMBER OF OBSERVATIONS

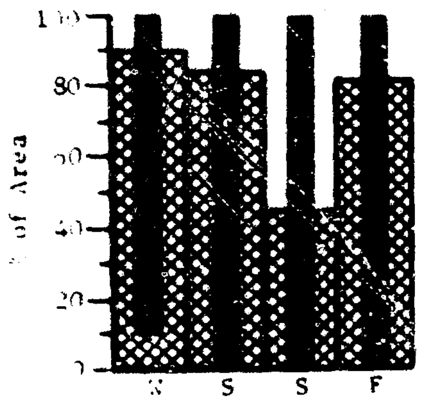
Winter	64
Spring	71
Summer	12*
Fall	No Data

SECTOR DATA

Latitude	75° - 80°N
Longitude	0° - 22.5°E
Area (n mi^2)	90,000

Ice Characteristics
Sector C-1A

*Data too limited to be significant

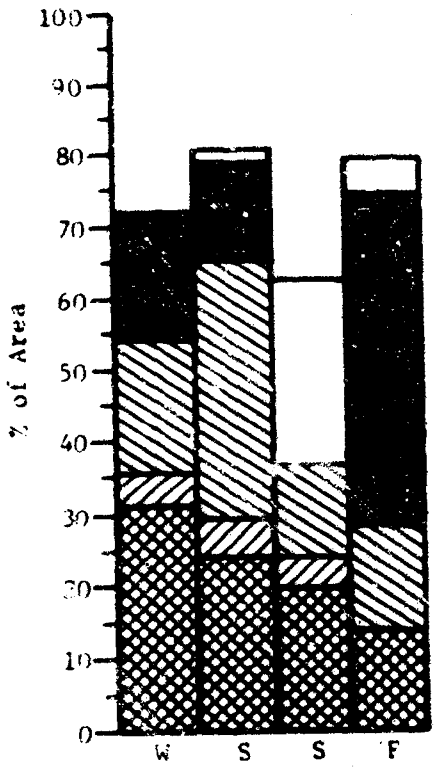


Average Ice Concentration

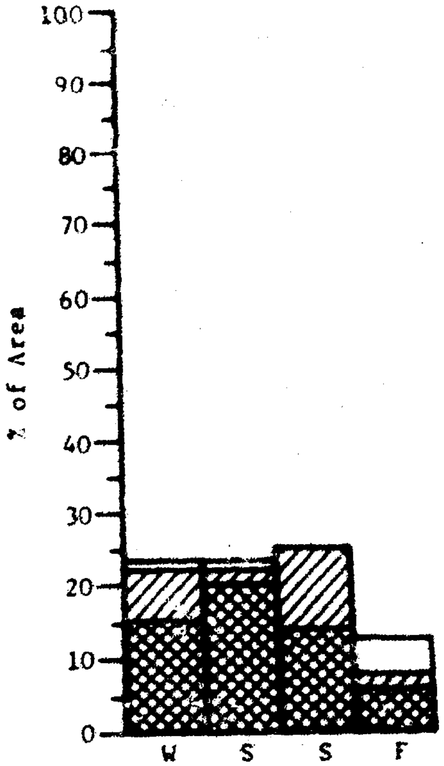
	W	S	S	F
Cracks	21	13		16
Polynyi				16
Pools	2			
Leads				2
Open Water	35	56	74	39
No Ice		2	26	5

Water Openings by
% Observations

Data Source: Birds Eye



Principal Types of Ice



Dominant Ice Topography

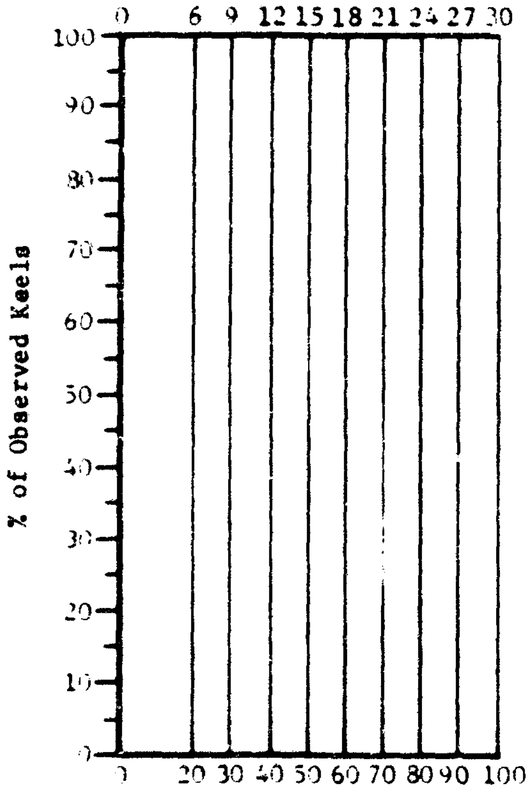
NUMBER OF OBSERVATIONS

Winter 82
Spring 94
Summer 23
Fall 44

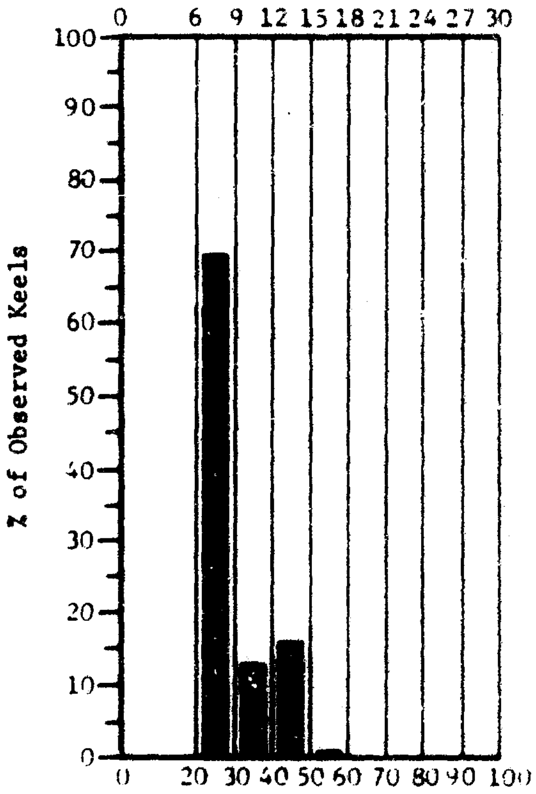
SECTOR DATA

Latitude 85° 75° - 80°N
Longitude 0° 22.5° - 45°E
Area (n mi^2) 93,000

Ice Characteristics
Sector C-18



WINTER



SUMMER

	W	S
Openings		7
Ice		93
Keels		7

% of Observed Track

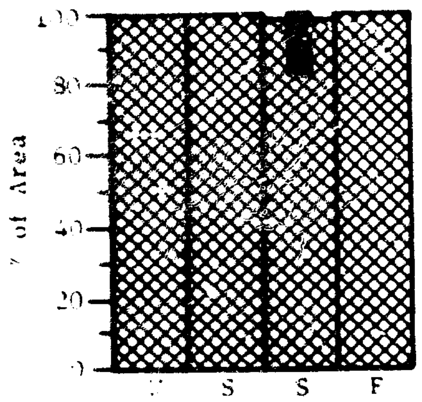
Observations	W	S
Track Segments	No	2
Total Length (n mi)	Data	21

Data Source: USS Sargo and USS Seadragon 1960

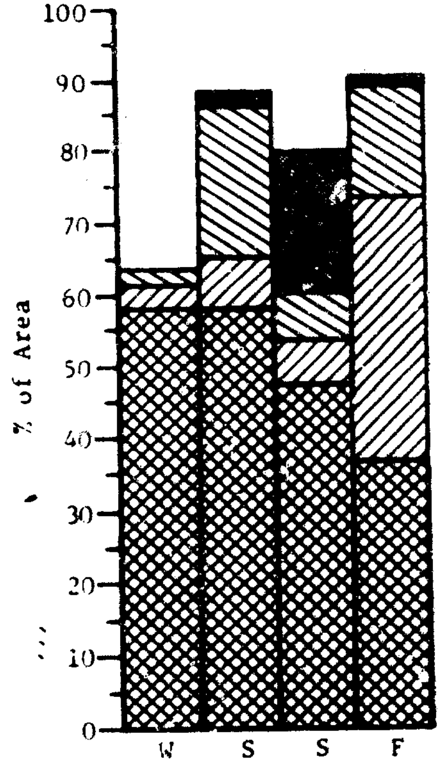
SECTOR DATA

Latitude 75° - 80°N
Longitude 135° - 157.5°E
Area (n mi^2) 93,000

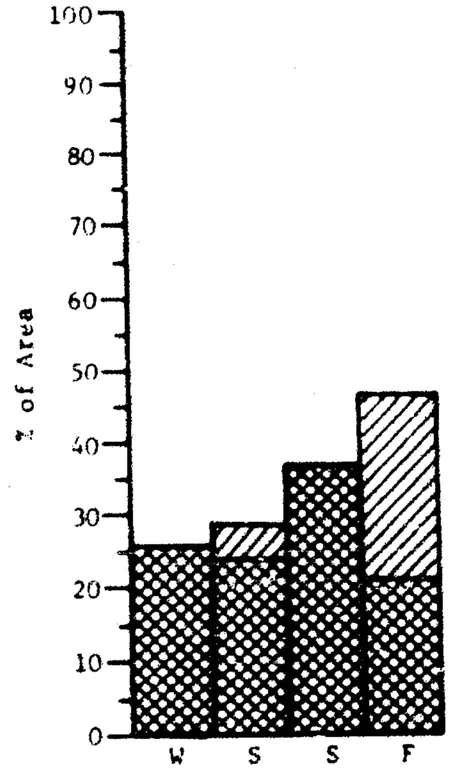
Ice Characteristics
Sector C-2C



Average Ice Concentration



Principal Types of Ice



Dominant Ice Topography

	W	S	S	F
Cracks	97	42	76	61
Polynyi		2		
Pools				
Leads		27		22
Open Water		3	8	
No Ice				

Water Openings by % Observations

Data Source: Birds Eye

NUMBER OF OBSERVATIONS

Winter 33

Spring 60

Summer 25

Fall 18*

*Data too limited to be significant

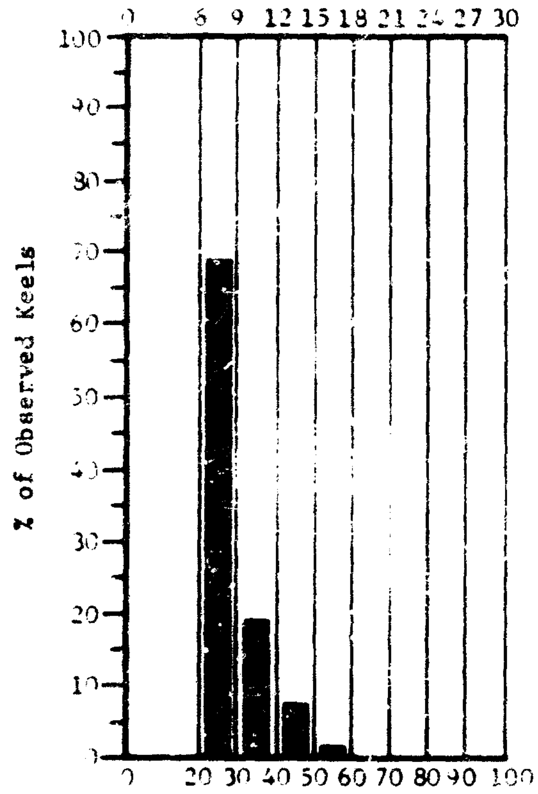
SECTOR DATA

Latitude 85° 75° - 80°N

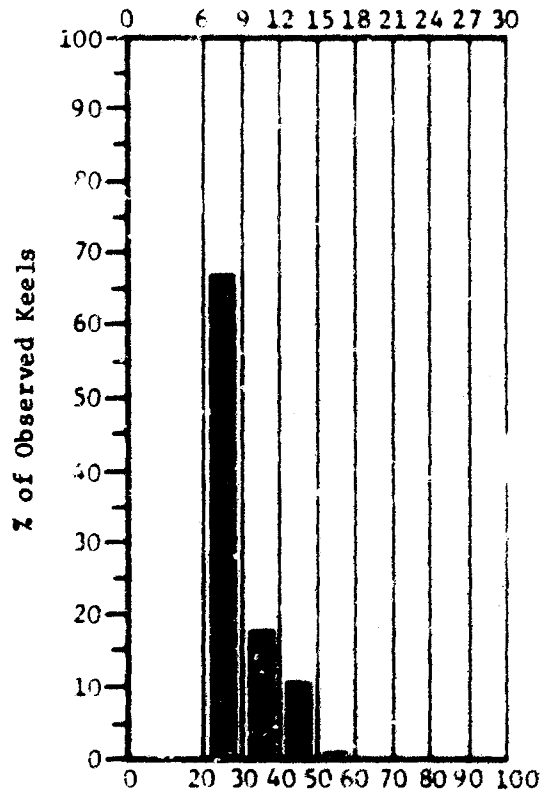
Longitude 0° 157.5°E - 180°

Area (n mi²) 93,000

Ice Characteristics
Sector C-2D



WINTER



SUMMER

	W	S
Openings	2	2
Ice	98	98
Keels	9	8

% of Observed Track

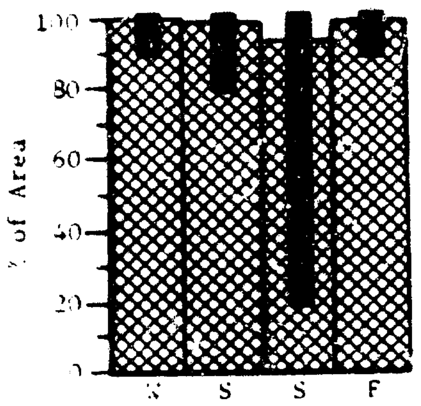
Observations	W	S
Track Segments	4	3
Total Length (n mi)	65	36

Data Source: USS Sargo and USS Seadragon 1960

SECTOR DATA

Latitude 75° - 80°N
Longitude 157.5°E - 180°
Area (n mi^2) 93,000

Ice Characteristics
Sector C-2D

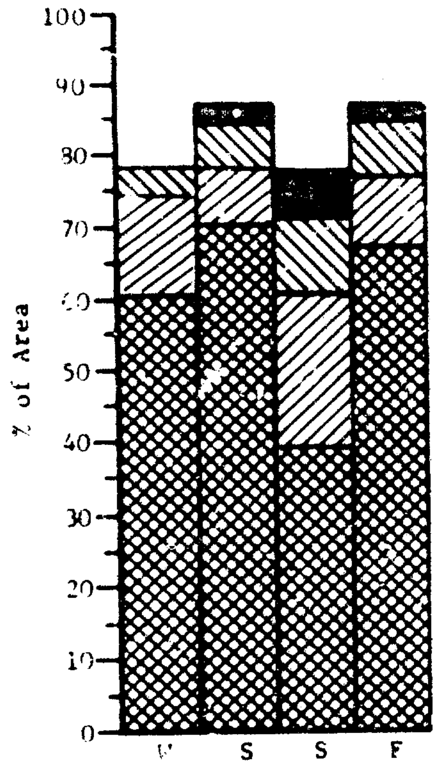


Average Ice Concentration

	W	S	S	F
Cracks	40	38	15	54
Polynyi				
Pools				
Leads		2	1	
Open Water	<1	12	57	41
No Ice				

Water Openings by % Observations

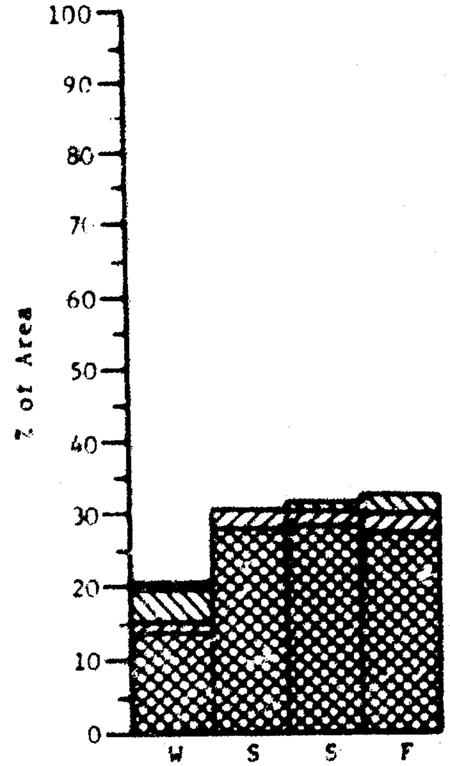
Data Source: Birds Eye



Principal Types of Ice

NUMBER OF OBSERVATIONS

Winter	152
Spring	109
Summer	243
Fall	173



Dominant Ice Topography

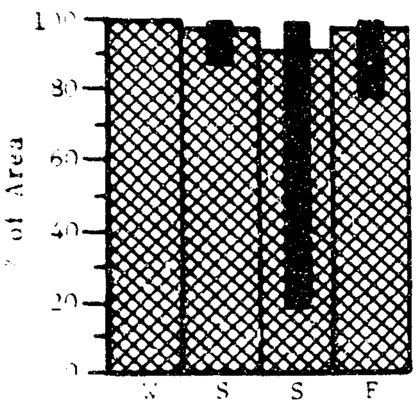
SECTOR DATA

Latitude 75° - 90°N

Longitude 180° - 157.5°W

Area (n mi^2) 93,000

Ice Characteristics
Sector C-3A

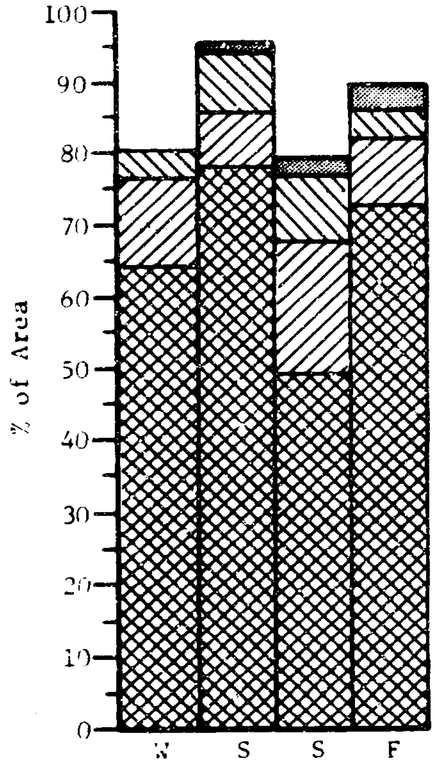


Average Ice Concentration

	W	S	S	F
Cracks	39	39	23	48
Polynyi			9	
Pools				
Leads				
Open Water	1	14	53	
No Ice				

Water Openings by % Observations

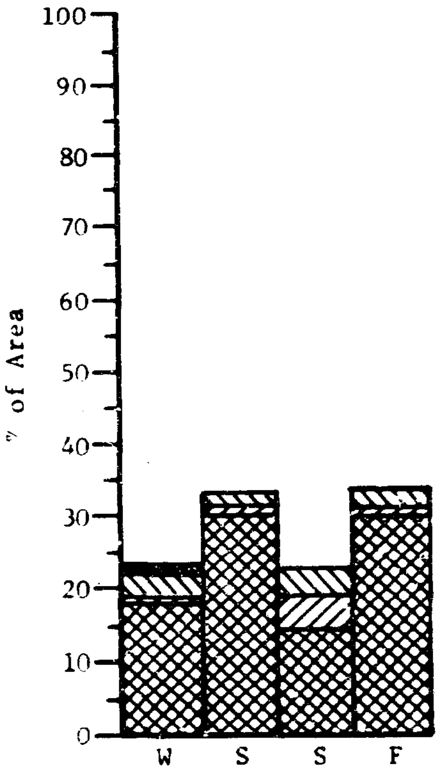
Data Source: Birds Eye



Principal Types of Ice

NUMBER OF OBSERVATIONS

Winter	213
Spring	153
Summer	182
Fall	238



Dominant Ice Topography

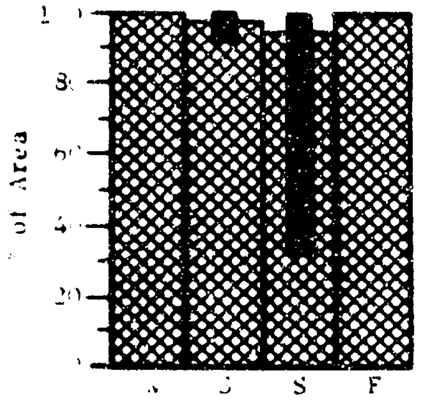
SECTOR DATA

Latitude 75° - 80°N

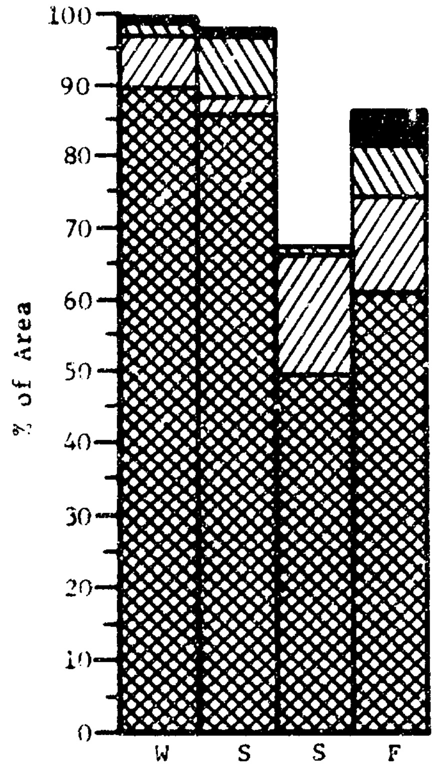
Longitude 157.5° - 135°W

Area (n mi^2) 93,000

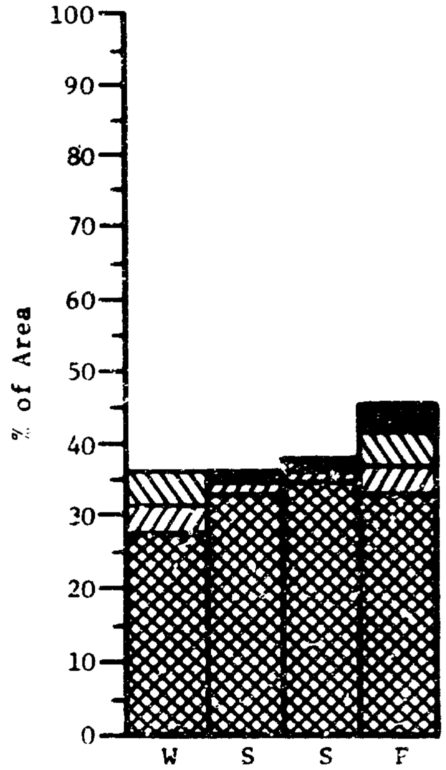
Ice Characteristics
Sector C-8



Average Ice Concentration



Principal Types of Ice



Dominant Ice Topography

	W	S	S	F
Cracks	41	35	25	38
Polynyi				
Pools				
Leads		6		2
Open Water		27	42	
No Ice				

Water Openings by % Observations

Data Source: **Birds Eye**

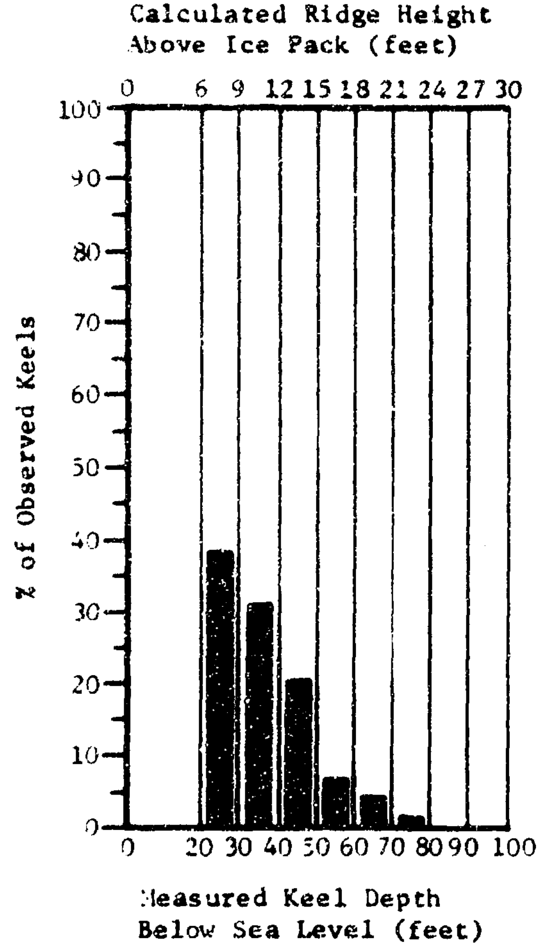
NUMBER OF OBSERVATIONS

Winter	80
Spring	127
Summer	172
Fall	94

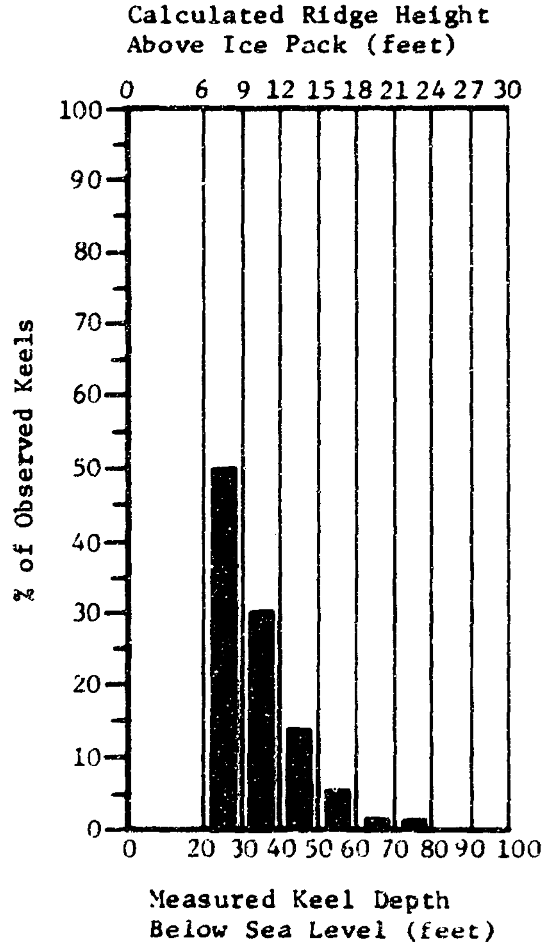
SECTOR DATA

Latitude	75° - 80°N
Longitude	135° - 90°W
Area (n mi^2)	88,000

Ice Characteristics
Sector C-3C



WINTER



SUMMER

	W	S
Openings	<1	40
Ice	100	60
Keels	30	20

% of Observed Track

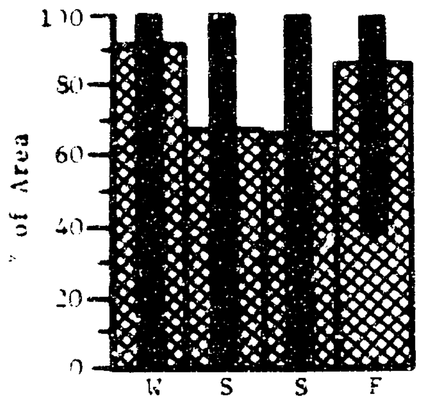
Observations	W	S
Track Segments	2	2
Total Length (n mi)	31	32

Data Source: USS Sargo and USS Seadragon 1960

SECTOR DATA

Latitude 75° - 80°N
Longitude 135° - 90°W
Area (n mi^2) 88,000

Ice Characteristics
Sector C-3C

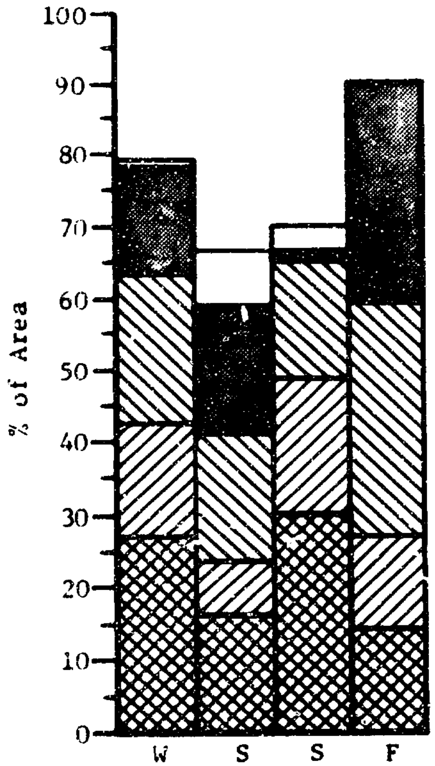


Average Ice Concentration

	W	S	S	F
Cracks	36	3	2	10
Polynyi	1			
Pools				
Leads		1		
Open Water	32	65	79	65
No Ice	1	8	4	

Water Openings by % Observations

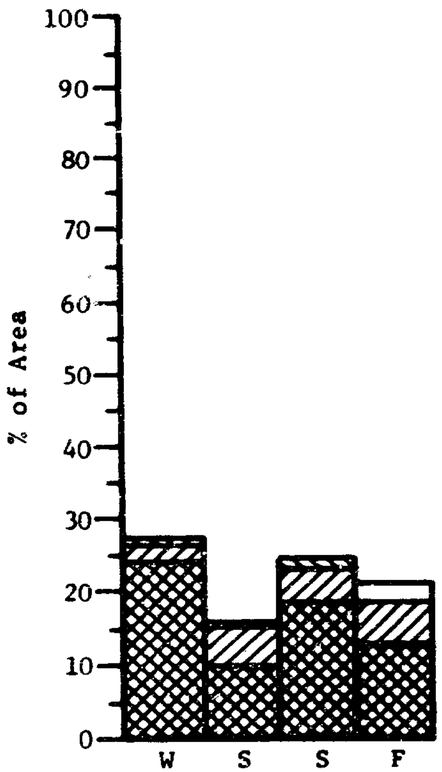
Data Source: Birds Eye



Principal Types of Ice

NUMBER OF OBSERVATIONS

Winter	97
Spring	93
Summer	134
Fall	38



Dominant Ice Topography

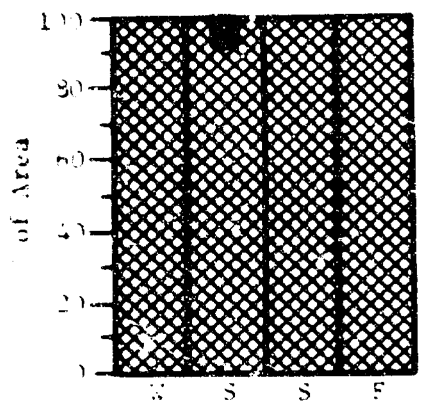
SECTOR DATA

Latitude 85° 75° - 80°N

Longitude 0° 22.5°W - 0°

Area (n mi^2) 92,000

Ice Characteristics
Sector C-4D

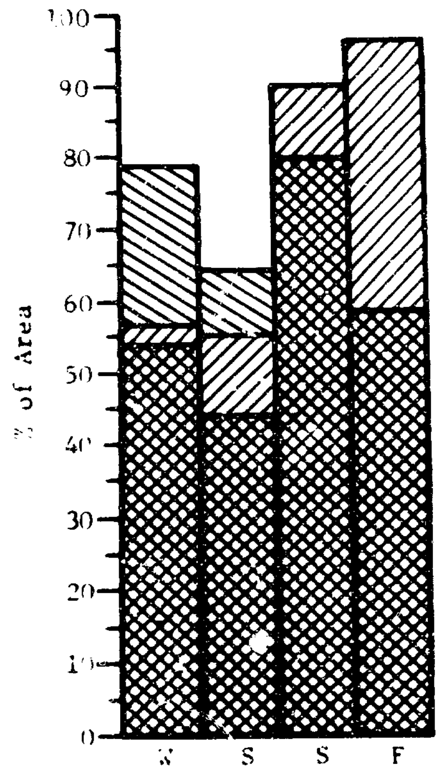


Average Ice Concentration

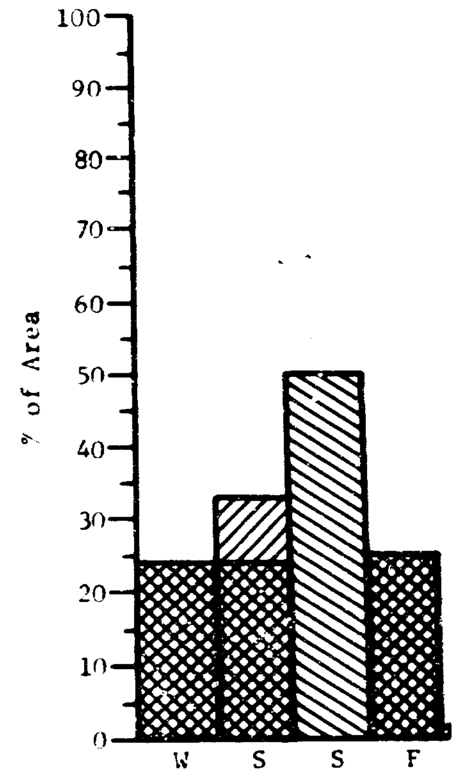
	W	S	S	F
Cracks	100	16	100	100
Polynyi				
Pools				
Leads				
Open Water		3		
No Ice				

Water Openings by % Observations

Data Source: **Birds Eye**



Principal Types of Ice



Dominant Ice Topography

NUMBER OF OBSERVATIONS

Winter	6*
Spring	31
Summer	2*
Fall	4*

***Data too limited to be significant**

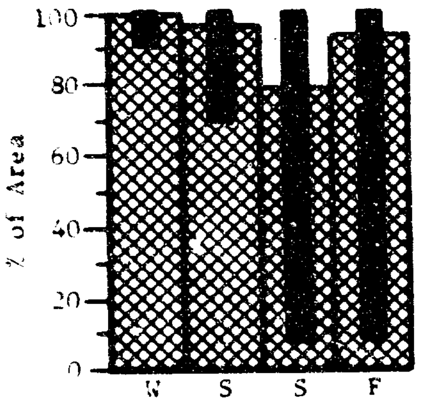
SECTOR DATA

Latitude 85° 70° - 75°N

Longitude 0° 157.5° - 180°

Area (n mi^2) 120,000

Ice Characteristics
Sector D-2D

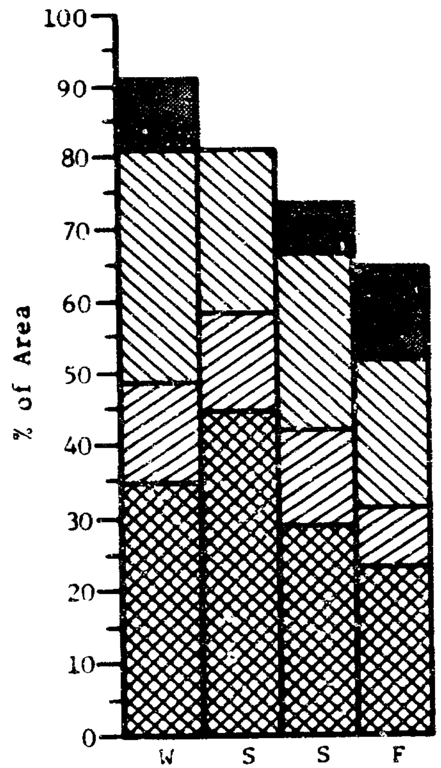


Average Ice Concentration

	W	S	S	F
Cracks	56	50	9	45
Polynyi			1	
Pools				1
Leads		4		4
Open Water	5	26	65	13
No Ice				

Water Openings by % Observations

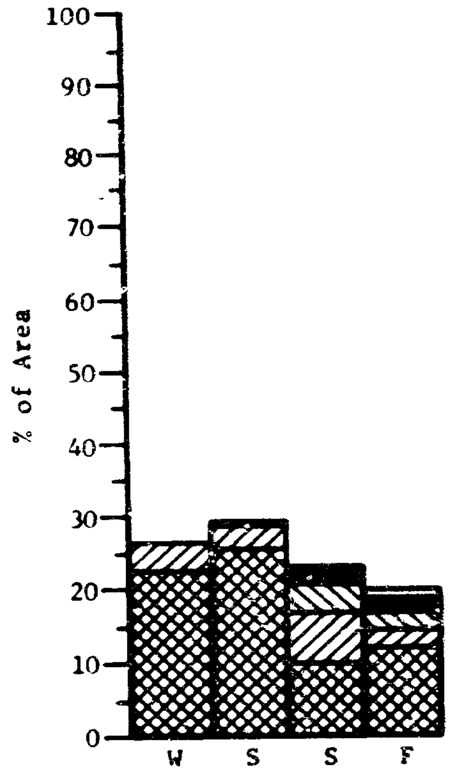
Data Source: Birds Eye



Principal Types of Ice

NUMBER OF OBSERVATIONS

Winter	196
Spring	131
Summer	191
Fall	195

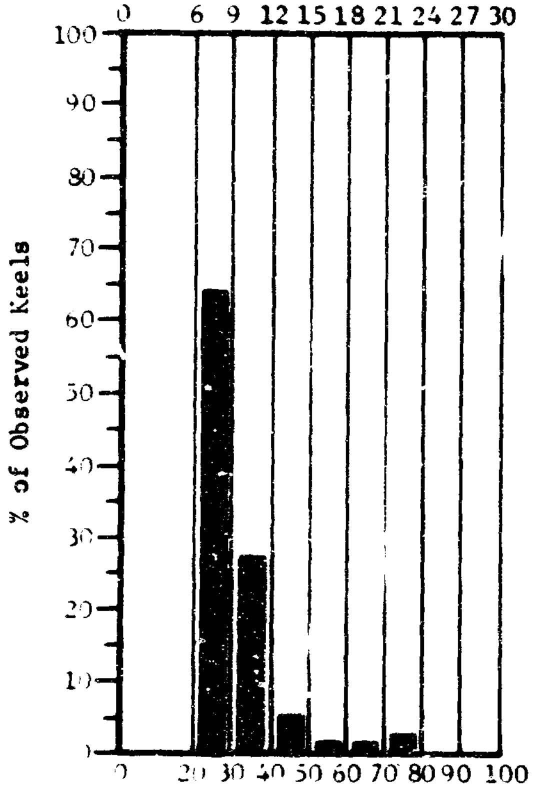


Dominant Ice Topography

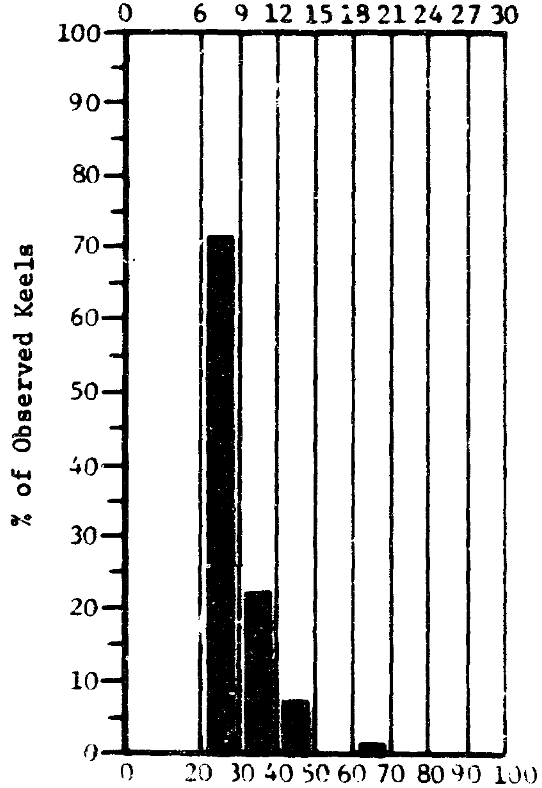
SECTOR DATA

Latitude	70° - 75°N
Longitude	180° - 157.5°W
Area (n mi^2)	121,000

Ice Characteristics
Sector D-3A



WINTER



SUMMER

	W	S
Openings	2	9
Ice	98	91
Keels	12	7

% of Observed Track

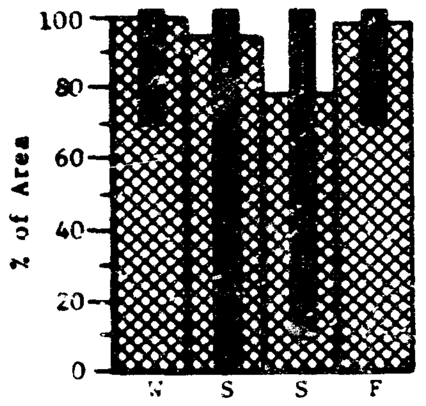
Observations	W	S
Track Segments	3	5
Total Length (n mi)	35	45

Data Source: USS Sargo and USS Seadragon 1960

SECTOR DATA

Latitude 70° - 75°N
Longitude 180° - 157.5° W
Area (n mi^2) 121,000

Ice Characteristics
Sector D-3A

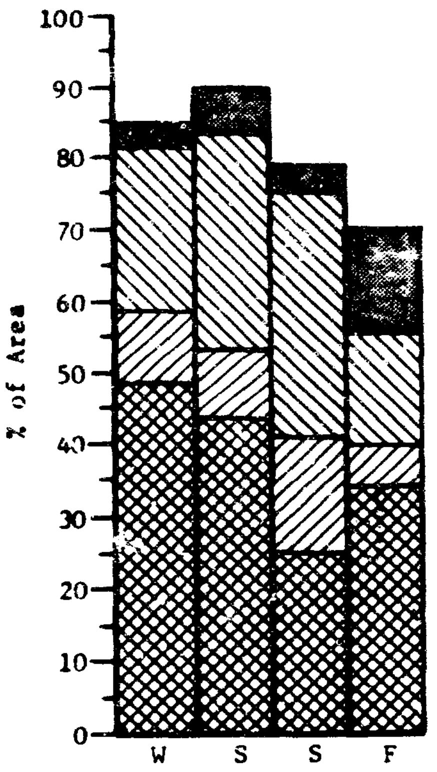


Average Ice Concentration

	W	S	S	F
Cracks	47	19	18	48
Polynyi		<1	1	
Pools			2	1
Leads	<1	3	<1	<1
Open Water	<1	22	57	13
No Ice		1		

Water Openings by % Observations

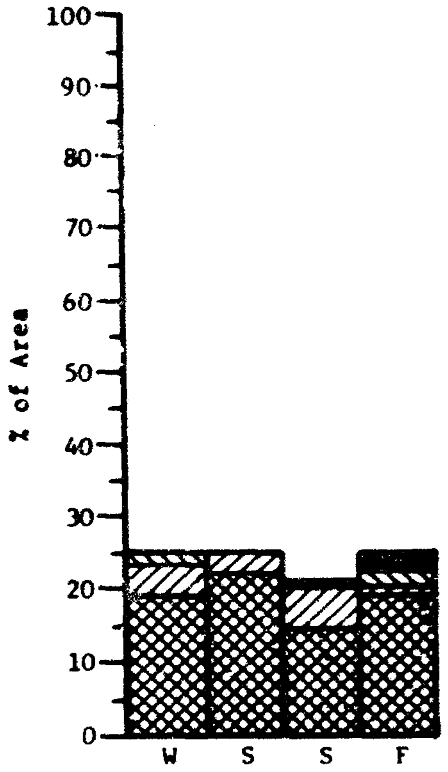
Data Source: Birds Eye



Principal Types of Ice

NUMBER OF OBSERVATIONS

Winter	241
Spring	220
Summer	227
Fall	238



Dominant Ice Topography

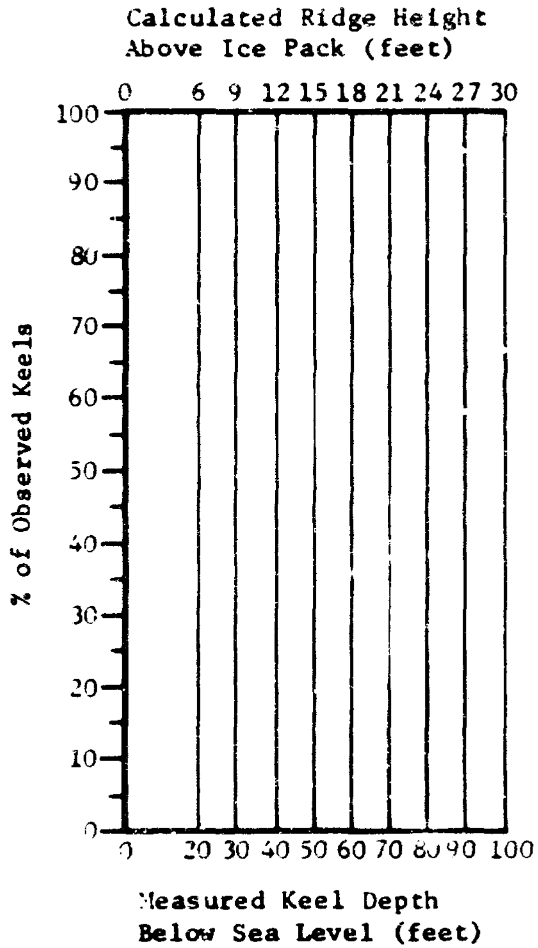
SECTOR DATA

Latitude 70° - 75°N

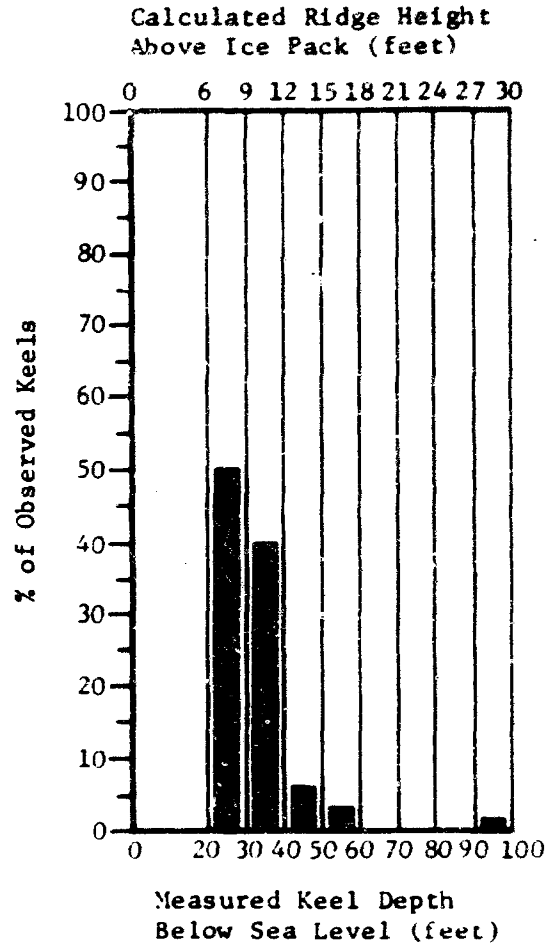
Longitude 157.5° - 135°W

Area (n mi^2) 122,000

Ice Characteristics
Sector D-3B



WINTER



SUMMER

	W	S
Openings		10
Ice		100
Keels		0

% of Observed Track

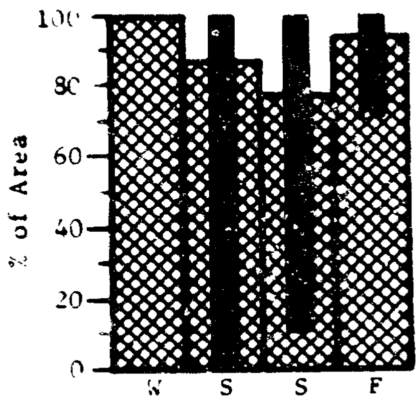
Observations	W	S
Track Segments	No	1
Total Length (n mi)	Data	9

Data Source: USS Sargo and USS Seadragon 1960

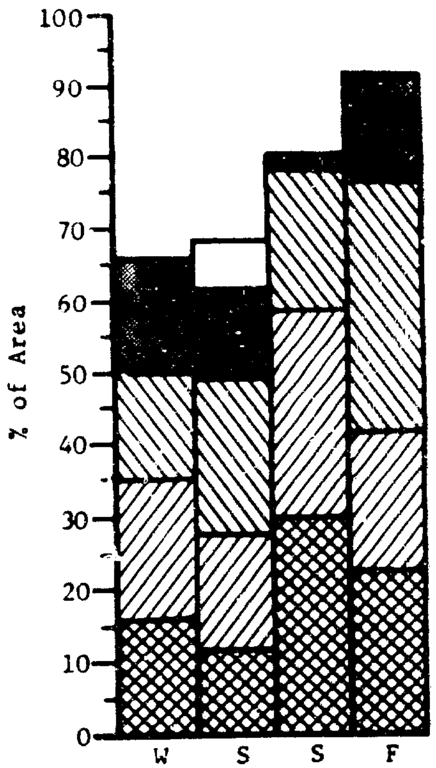
SECTOR DATA

Latitude 70° - 75°N
Longitude 157.5° - 135°W
Area (n mi^2) 122,000

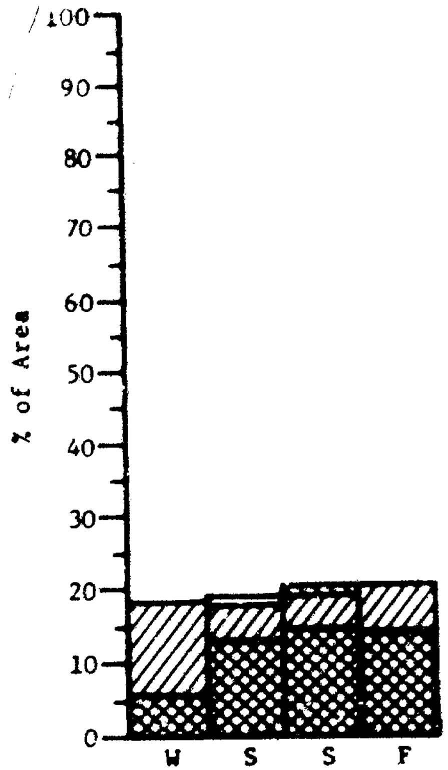
Ice Characteristics
Sector D-3B



Average Ice Concentration



Principal Types of Ice



Dominant Ice Topography

	W	S	S	F
Cracks	50	12	20	9
Polynyi				
Pools				
Leads	10	5		4
Open Water		37	61	22
No Ice		6		

Water Openings by % Observations

Data Source: Birds Eye

NUMBER OF OBSERVATIONS

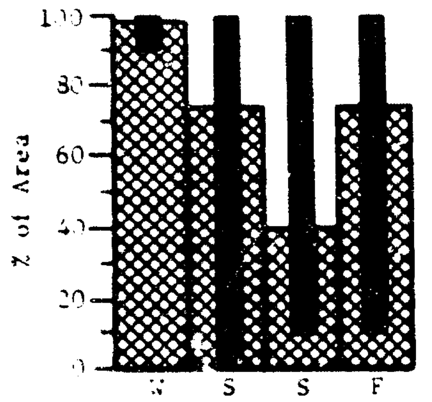
Winter	10*
Spring	64
Summer	94
Fall	24

*Data too limited to be significant

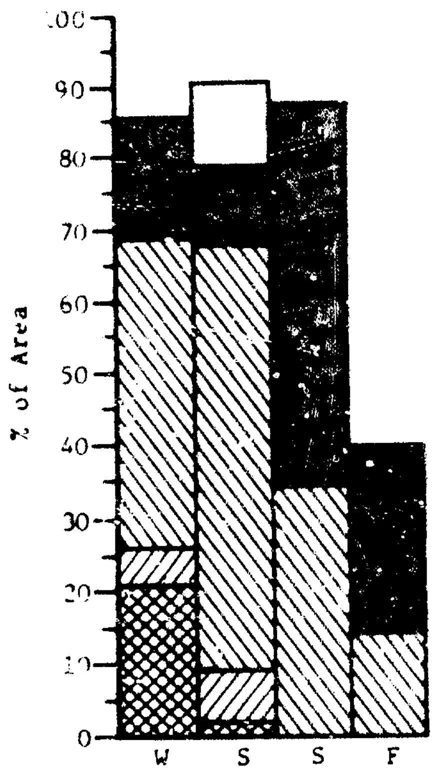
SECTOR DATA

Latitude 85°	70° - 75°N
Longitude 0°	135° - 125°W
Area (n mi^2)	55,000

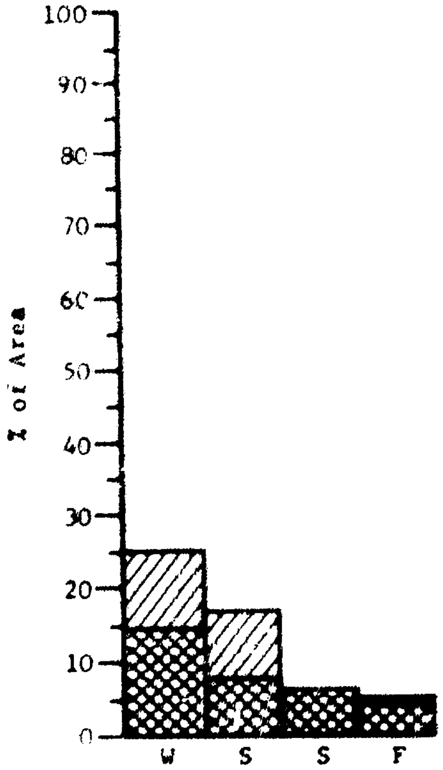
Ice Characteristics
Sector D-3C



Average Ice Concentration



Principal Types of Ice



Dominant Ice Topography

	W	S	S	F
Cracks	60	30		
Polynyi				
Pools				
Leads				
Open Water	15	42	11	73
No Ice		12		

Water Openings by % Observations

Data Source: Birds Eye

NUMBER OF OBSERVATIONS

Winter 26*

Spring 33

Summer 9*

Fall 13*

*Data too limited to be significant

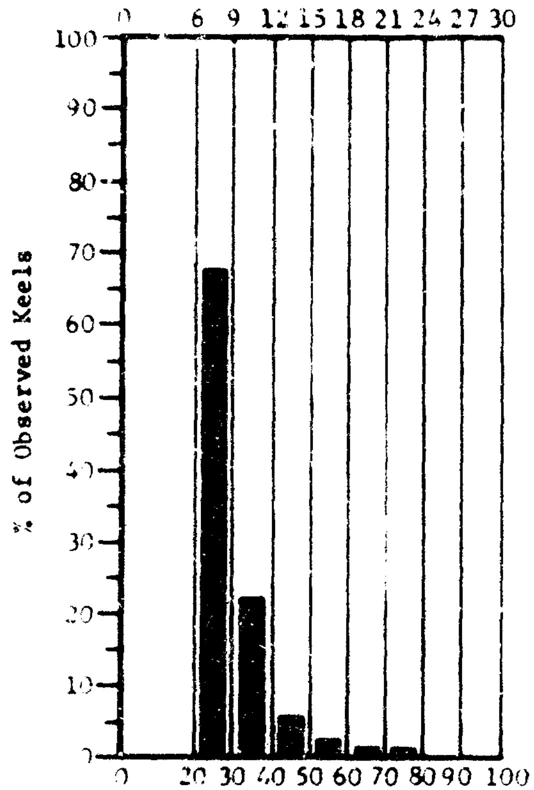
SECTOR DATA

Latitude Bering St. - 80°N

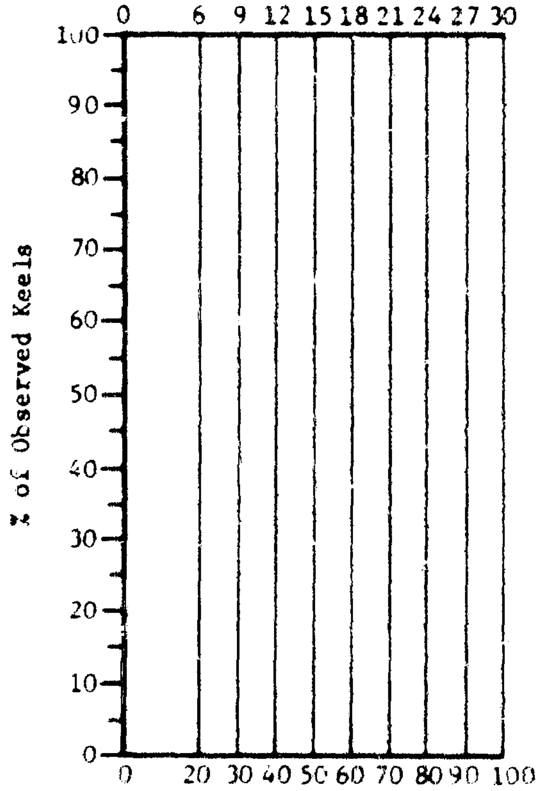
Longitude 180° - 157.5°W

Area (n mi^2) 63,000

Ice Characteristics
Sector E-3A



WINTER



SUMMER

	W	S
Openings	5	
Ice	95	
Keels	23	

% of Observed Track

Observations	W	S
Track Segments	3	No
Total Length (n mi)	25	Data

Data Source: USS Sargo and USS Seadragon 1960

SECTOR DATA

Latitude Bering St.-70°N
Longitude 180° to 157.5°W
Area (n mi^2) 63,000

Ice Characteristics
Sector E-3A

As a result of this continuous movement, it is misleading to speak of a permanent pack in the central arctic; rather this portion of the pack is an area where ice impenetrable to ships is always present. In addition to the water influx from the Atlantic, there is a substantial flow introduced from the large rivers that empty into the basin. The principal outflow from the basin occurs in the southward water transport of the East Greenland Current moving between Svalbard and Greenland. Additional outflow from the basin occurs in the form of southward and eastward moving currents through the islands of the Canadian Archipelago.

These outflows from the arctic tend to carry with them portions of the pack ice, creating an extensive tongue of ice along the northeast coast of Greenland and causing persistent plugging of the narrow waters in the western and northern entrances to the Canadian Archipelago.

6.5.2 Pack Boundaries

Ice condition in the Arctic Ocean and the adjacent seas varies seasonally and, perhaps more importantly, varies from year to year. The causes of the variations are complex, but they can be considered to result from persistent weather conditions such as warming or cooling trends that may occur over periods of many years and on which are superimposed the annual changes.

In the early fall, ice begins to form along the shorelines and in the rivers. As the winter season approaches this ice continues to expand and thicken. The polar pack repeatedly moves on and off the shore, grinding this new ice and causing it to pile on shore. When the pack moves offshore, leads are formed between the shore ice and the pack which are rapidly frozen over. By early in December the ice thickness is usually sufficient to reach the bottom in the shallow coastal waters, and the ice becomes frozen to the bottom. Maximum ice thickness is usually reached in April or May when the first thaw begins to set in.

Maximum extent of the polar pack and the land-fast ice normally occurs in April or May, at which time essentially the entire Arctic Basin as well as the east coast of Greenland, the Canadian Archipelago, and much of the Bering Sea are covered. The seas along the Siberian coast are entirely ice bound with the exception of the western and southern portions of the Barents Sea (Reference 5).

The presence of the ice pack and the character of the ice is of critical importance to the operation of surface ships in the arctic, both from the standpoint of ship design and for a determination of the certainty that a given ship can be sent into a given area. Figures 6-3 to 6-6 show the ice extremes. On these charts the areas where ice has always been reported as less than 1/10 coverage can be considered as always open to any ship for unimpeded operation. In areas identified

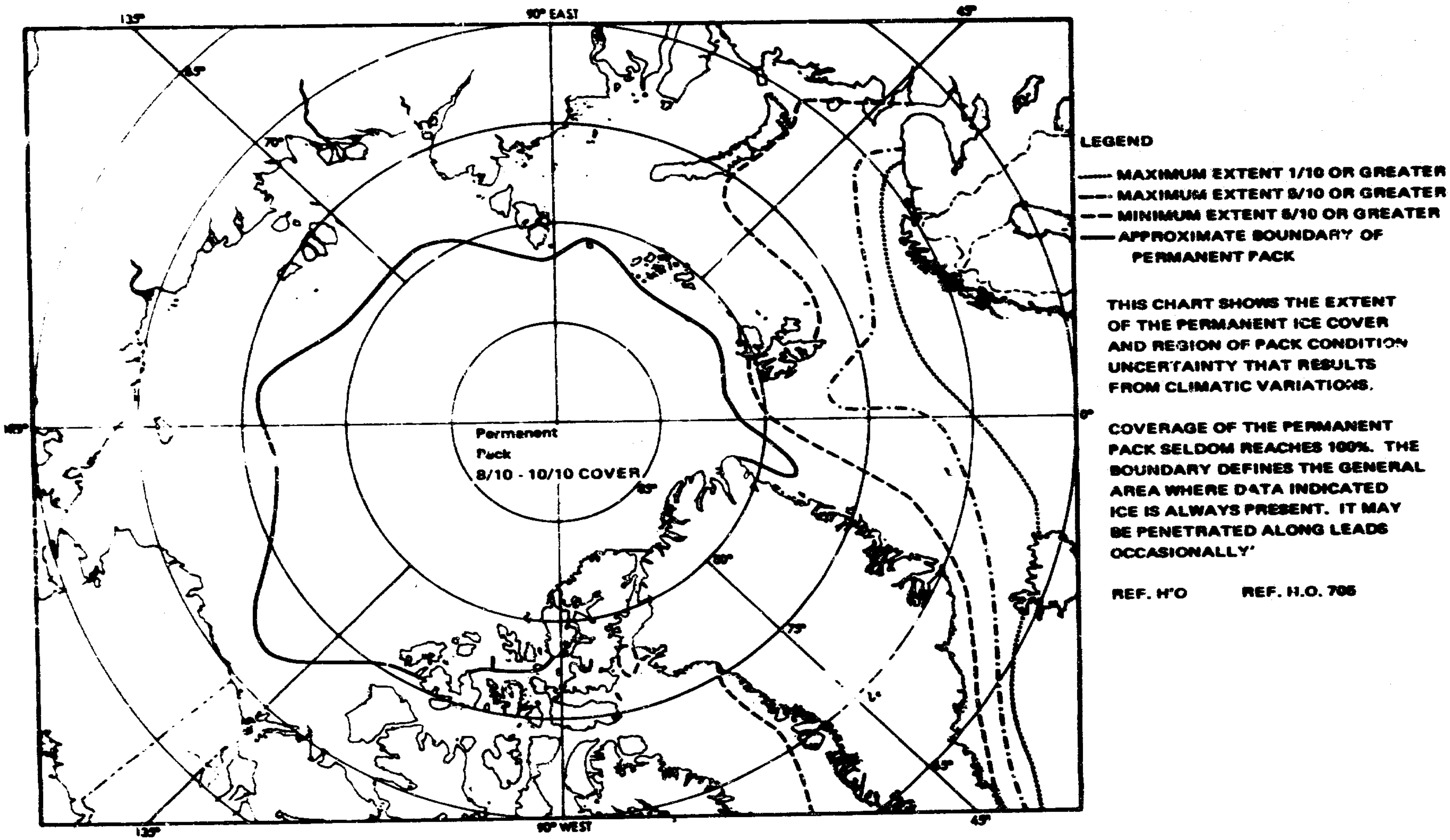
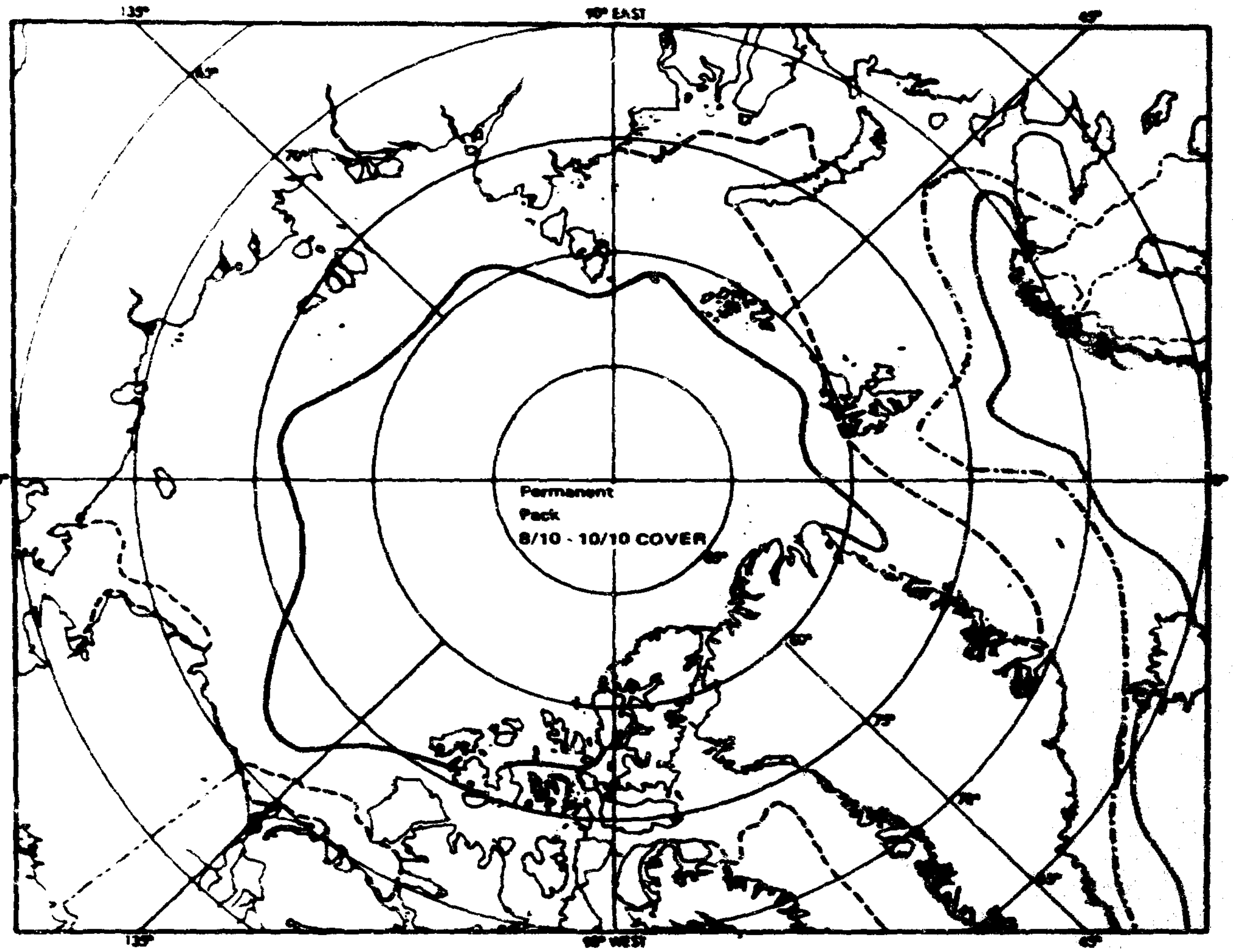


Figure 6-3: PACK EXTENT WINTER



LEGEND

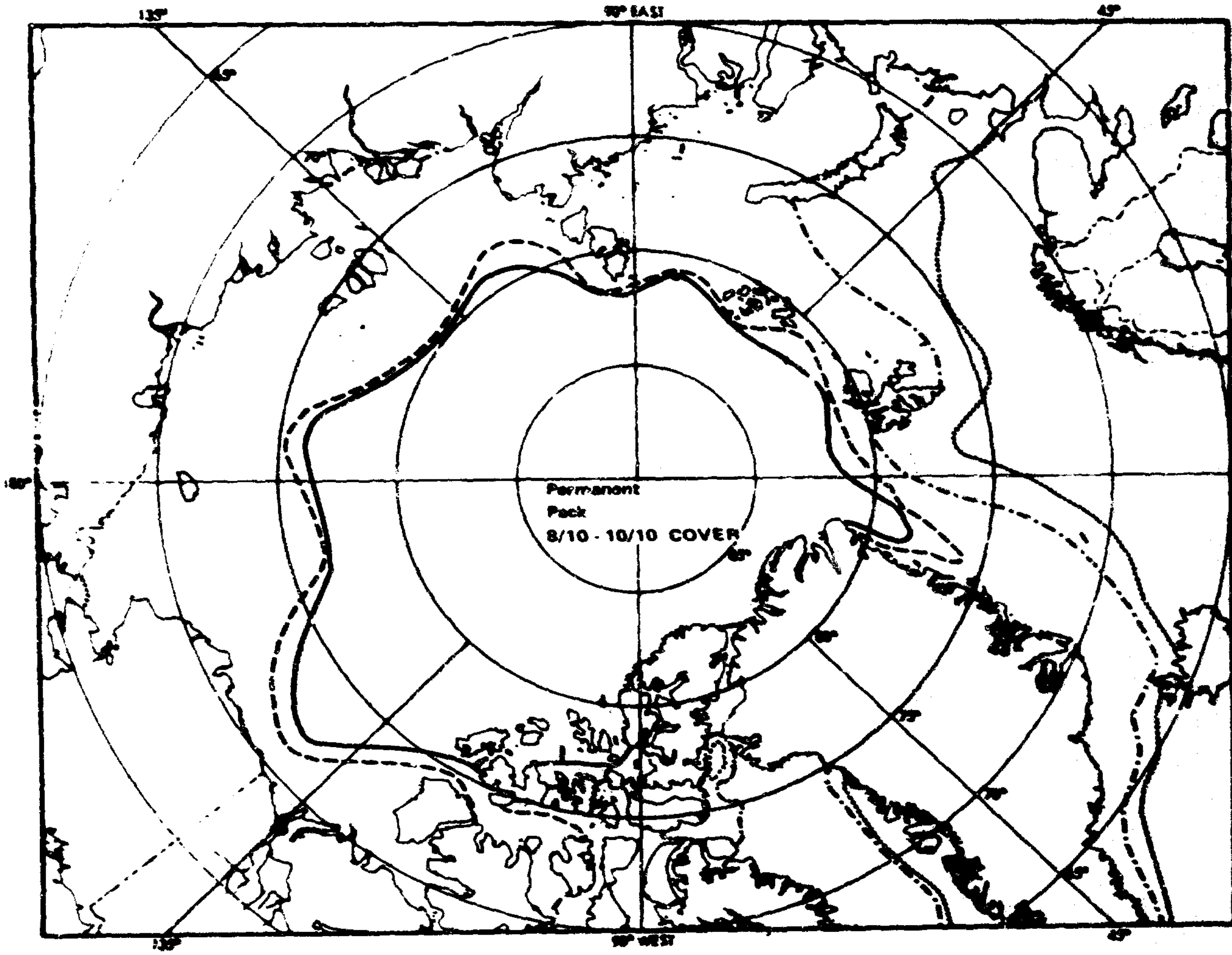
- MAXIMUM EXTENT 1/10 OR GREATER
- MAXIMUM EXTENT 5/10 OR GREATER
- MINIMUM EXTENT 5/10 OR GREATER
- APPROXIMATE BOUNDARY OF PERMANENT PACK

THIS CHART SHOWS THE EXTENT OF THE PERMANENT ICE COVER AND REGION OF PACK CONDITION UNCERTAINTY THAT RESULTS FROM CLIMATIC VARIATIONS.

COVERAGE OF THE PERMANENT PACK SELDOM REACHES 100%. THE BOUNDARY DEFINES THE GENERAL AREA WHERE DATA INDICATES ICE IS ALWAYS PRESENT. IT MAY BE PENETRATED ALONG LEADS OCCASIONALLY.

REF. H.O. 705

Figure 6-4: PACK EXTENT SPRING



LEGEND

- MAXIMUM EXTENT 1/10 OR GREATER
- MAXIMUM EXTENT 8/10 OR GREATED
- MINIMUM EXTENT 8/10 OR GREATER
- APPROXIMATE BOUNDARY OF PERMANENT PACK

THIS CHART SHOWS THE EXTENT OF THE PERMANENT ICE COVER AND REGION OF PACK CONDITION UNCERTAINTY THAT RESULTS FROM CLIMATIC VARIATIONS.

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REF. H.O. 705

Figure 6-5: PACK EXTENT SUMMER

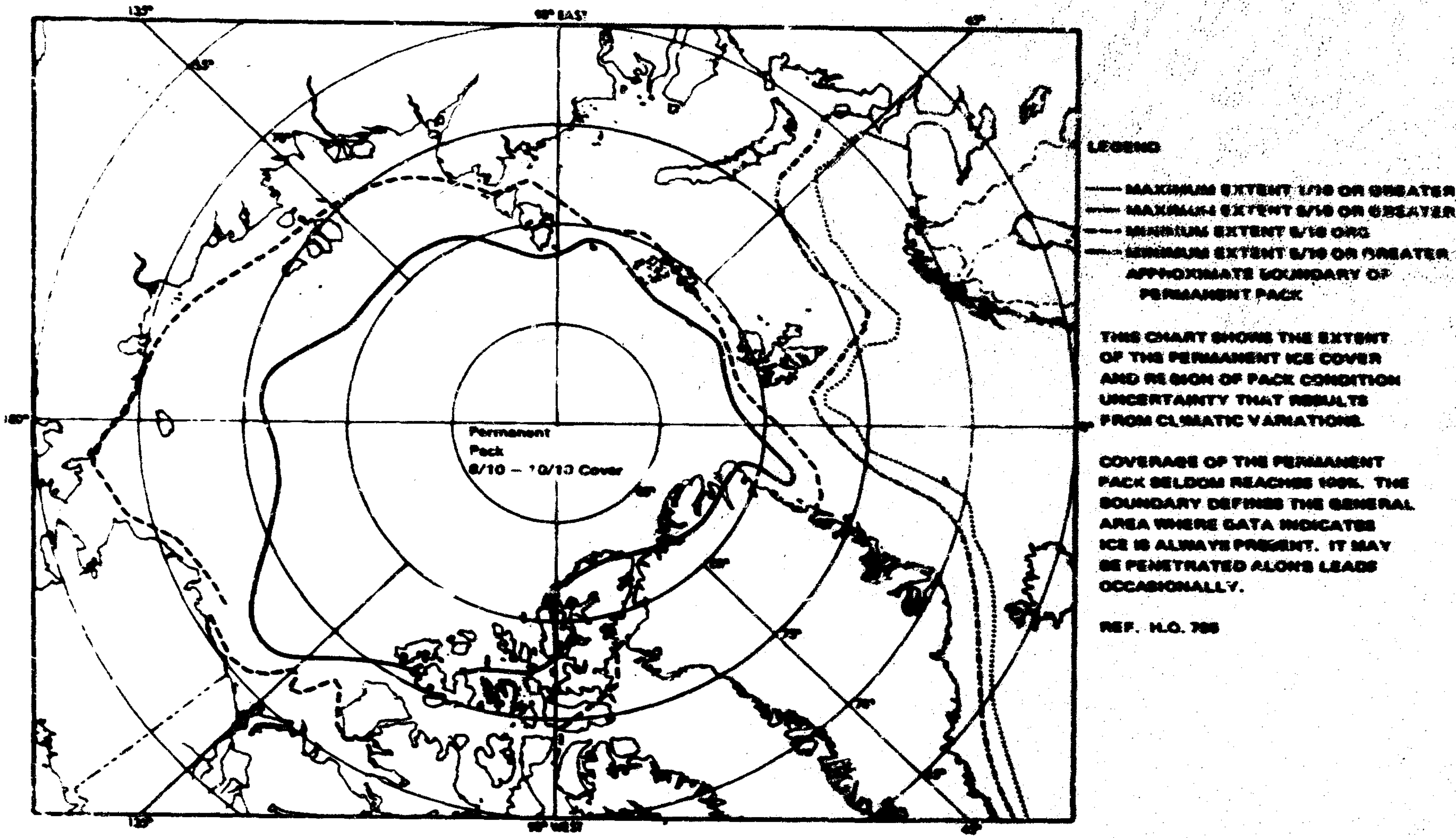

Figure 6-6: PACK EXTENT FALL

as 5/10 coverage, ice-strengthened ships can have generally unimpeded operation, and unstrengthened ships must sacrifice mobility and speed.

Because of climatic changes some years may find this area partially or entirely ice free. Beyond the second area is a region that has the greatest variability in that the coverage may reach either 10/10 or less than 1/10. Consistently reliable penetration is doubtful even with adequately designed vessels. Penetration by any vessel preceded by adequate scouting may be possible, but freedom of mobility is unlikely.

The area surrounding the permanent ice pack includes the portion of the pack where the ice coverage is always greater than 5/10. Passage of ships into this area and into the permanent pack is highly dependent on specific ice conditions and the availability of leads. Only ice breakers or specially designed ships have any degree of safety in attempting penetration. The likelihood of being frozen in the ice is high. On specific occasions penetrations as far north as 80° has been achieved, but such penetration is unusual (Reference 5).

Figure 6-3, which shows the winter pack extent, approximates the limiting conditions for ship operation when all-year operation with full freedom of mobility is desired.

6.5.3 Ice Concentration

The extent of the ice pack, as defined by the pack boundaries, gives a gross indication of the ice concentration; however, to be useful more detailed information is necessary.

The concentration of the ice is a measure of the areal extent of ice present in a given area to the total areal extent of both ice and water. The usual method of reporting concentration is in tenths. By definition open water consists of less than 1/10 cover, while a very close pack or total ice cover consists of 10/10 cover. (References 2 and 13)

The average ice concentration is consistently in the 9/10 to 10/10 range throughout the year north of about 75°, except in the Greenland and Barents Sea areas. The spread of concentrations reported increases in the spring and summer, generally reflecting the seasonal changes. South of 75° the winter concentration remains high to the pack edge, but generally shows a reduction to the 8/10 to 9/10 range in the spring and fall averages. Summer averages generally decrease to 7/10 or less. As might be expected, the variability of the concentrations reported increases in a pronounced fashion and includes some variation even during the winter months.

Concentration values obtained in the sectors bordering Svalbard and Greenland are probably too high since the edge of the ice usually cut through a portion of the sector and observations were concentrated over the ice-covered section.

The ice percentage given on the submarine charts represents a measure of the concentration; however, there is no distinction made between ice-covered and ice-free openings.

6.5.4 Pack Dynamics

The gross circulatory pattern of the water and ice in the arctic is part of the total dynamic complex of actions and forces that affect the ice pack.

A highly generalized chart of the arctic surface-water movements is shown in Section 8.3.4, Figure 8-17. The gross pattern as shown is fairly well understood; however, in much of the area the flow pattern is highly variable and short-term movements often show little resemblance to the indicated gross pattern. Movements of the ice pack generally follow the pattern of the water movement. Three main areas of ice movement as shown in Figure 6-7 are:

1) The Transpolar Drift Stream,

2) The Pacific Gyral,

3) The East Greenland Drift Stream.

The first two represent the principal areas and directions of movement within the Arctic Basin, while the latter represents the principal path of ice egress from the basin into the Atlantic.

The drift of ice floes and ice islands is exceedingly complex. The drift trajectories are often extremely chaotic and cannot be fitted into a simple drift model. There seems to be little doubt that wind and water stresses play a large part in this movement; however, the effects of the Coriolis force, boundary layer forces, gradient currents, and internal ice stresses also appear to have appreciable effects (Reference 6).

Since available navigation methods have been inadequate for determining detail movements, little is known regarding the short-term day-by-day motions. Using available information Dunbar and Wittman have determined the actual movement of many of the drift stations on an annual basis, as well as the net change in position. From this they have derived a "coefficient of meandering," which is a crude measure of the movement normal to the regular drift. Values for some of the

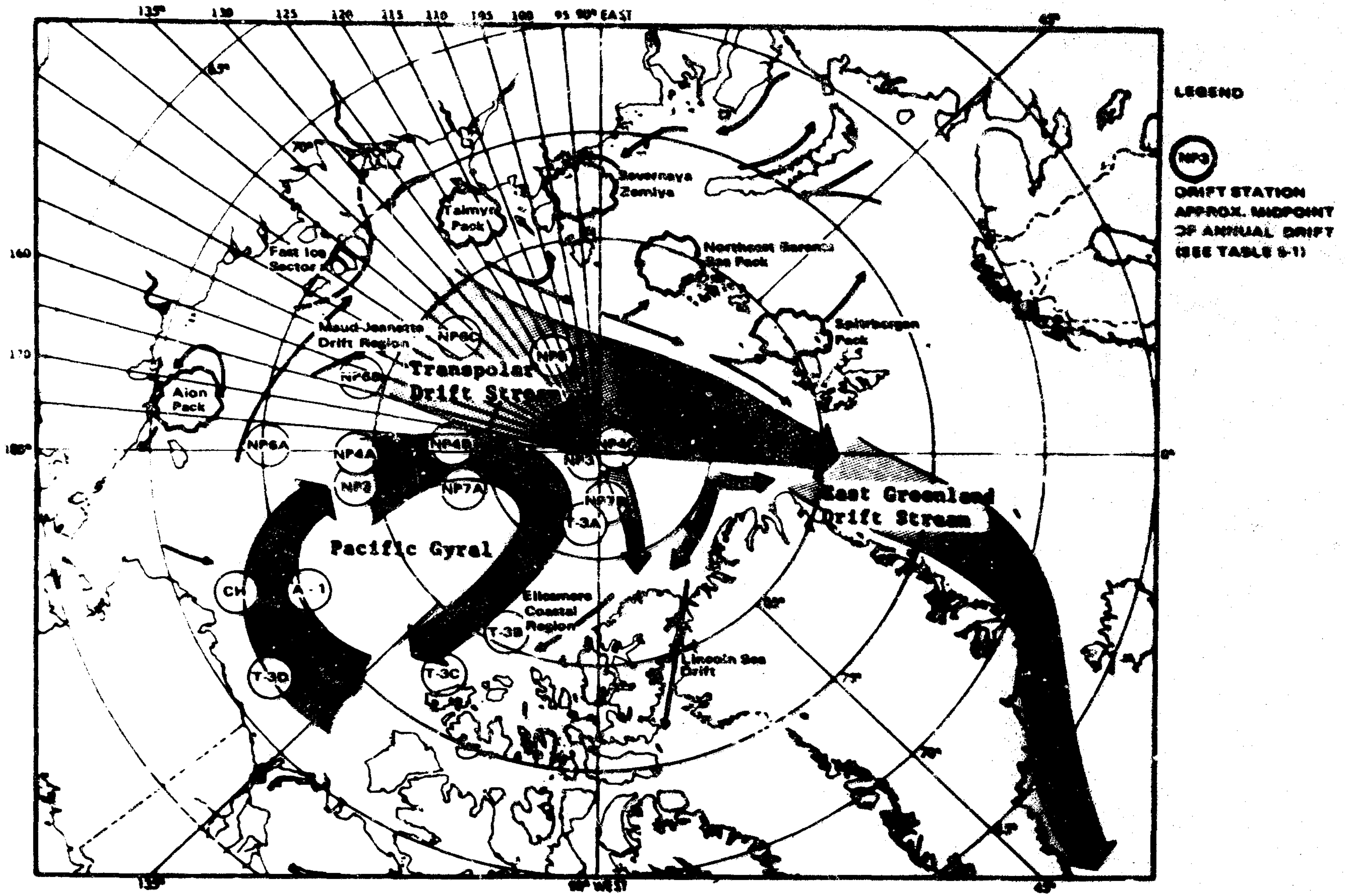

Figure 6-7: GENERALIZED ICE PACK MOVEMENT

stations during various years and in various positions in the arctic are given in Table 6-1. From this table it is apparent that the actual distance traveled by the various ice islands is generally 2 to 4 times the net rate of advance. Limited data from Station Charlie, which was located on a floe, shows a considerably higher rate of movement. This would seem to indicate that the size and mass of the ice islands may be sufficient to counteract a portion of the wind, current, and ice drag forces. If this is true, the coefficient of meandering of a given point on the ice pack might be expected to be greater than the values indicated in the table.

An important effect of erratic pack movement, as well as overall drift, is the impossibility of establishing a geographically fixed installation on the ice unless a capability is provided to maintain a reasonably continuous updating of position. This effectively rules out any form of fixed navigation or detection system located directly on the ice, and makes the use of the ice for long-term logistic support highly problematical. Other effects such as ice rupture obviously also affect such uses.

6.5.5 Sea Ice Development and Disintegration

Any operation in the arctic that requires transit over or penetration through the ice is affected by the stage of development or disintegration of the ice. During the development stages ice crystals are initially formed. Gradual thickening with age occurs, culminating in thick polar or arctic pack ice many years old in areas where the freezing cycle permits (Reference 2).

The stages of development include the following forms.

1) New Ice---New ice is classified into five kinds.

a) Ice Crystals---The first stage of sea ice, consisting of small spicules of thin plates suspended in the water. When formed under calm conditions, they speed the information of ice. Under turbulent conditions, they form streaks or bands oriented with the wind.

b) Slush---An accumulation of ice crystals, which remain separate or only slightly frozen together. Slush forms a thin layer, and gives the sea surface a greyish or leaden color. With light winds, no ripples appear, and even with a moderate wind, a dampening effect is noticeable. Average thickness is less than 2 inches.

c) Sludge---Consists of spongy whitish ice lumps a few centimeters across, usually an advanced stage of slush. It can also be formed from snow slush or ice lumps formed on the bottom of shallow waters which have emerged to the surface. Sludge may impede the progress of small craft, but usually offers little resistance to the passage of ships.

Table 6-1: DRIFT RATES FOR SELECTED DRIFT STATIONS

Station	Position	Year	Rate (nm day)		Coefficient *
			Actual	Net	Of Meandering
NP2		1950-51	3.7	0.9	4.1
NP4	A	1954-55	3.7	0.8	4.3
	B	1955-56	3.7	1.1	3.2
	C	1956-57	2.8	1.1	2.6
NP5		1955-56	3.7	1.2	3.1
NP6	A	1956-57	3.8	0.5	7.2
	B	1957-58	3.9	1.1	3.4
	C	1958-59	3.7	1.8	2.1
NP7	A	1957-58	2.9	0.6	4.3
	B	1958-59	2.4	1.2	2.0
T-3	A	1952-53	2.6	0.6	4.2
	B	1957-58	1.2	0.6	2.0
	C	1958-59	2.9	1.1	1.7
	D	1959-60	2.7	1.3	2.0
A-I (Arlis I)		1960-61	4.0	2.6	1.5
CH (Charlie)**		1959-60	5.1	0.5	10.0

NOTE: *Actual/Net
**Floe Station

After Dunbar and Wittman

d) Ice Rind---A thin, elastic crust of ice, formed by the freezing of slush on a calm sea surface. Since the average thickness is less than 2 inches, it is easily broken by wind or swell action. Color may vary from nearly black to a very light grey and, in good light conditions, will appear shiny.

e) Pancake---Of the same general stage of development as ice rind, but in pieces, usually approximately circular. Due to the action of wind and swell, the pieces strike each other, causing the rims of the pieces to be raised. These pieces of ice are usually 1 to 10 feet across and average less than 2 inches in thickness.

2) Young Ice---Newly formed ice, generally in the transition stage from ice rind or pancake ice to winter ice. Average thickness is from 2 to 6 inches. This ice is considered to be impassable, and unsafe for travel either by man or dogs, or in the case of aircraft, for ski or wheel landings.

3) Winter Ice---More or less unbroken ice of not more than one winter's growth, originating from young ice. Average thickness 6 inches to about 7 feet. Initially light grey to white, the coloration changes to tints of green and blue as the thickness becomes greater. Considered safe for traveling. Winter ice is classified as:

a) Medium Winter Ice---Winter ice 6 to 12 inches in thickness.

b) Thick Winter Ice---Winter ice more than 12 inches in thickness.

4) Polar Ice---Extremely heavy sea ice of more than one winter's growth, average less than 10 feet in thickness. Topography appears more or less level. Polar ice is usually pale to bright blue in color. It is classified as:

a) Young Polar Ice---Ice that has not melted during the first summer of its existence and has progressed into the second phase of increase. At the end of the second winter, it attains a thickness of up to 8 feet. It differs from ice 1 year old by a slightly greater portion showing above the water and also by smoother topography.

b) Arctic Pack---Almost salt-free ice more than 2 years old. The ice surface is undulating; and the topography, having melted more than once, is smoother. In the absence of significant snow cover, the ice appears as varying tints of blue.

Stages of disintegration include:

1) Snow Water on the Ice/Puddle---An accumulation of water on the ice surface takes form in:

   a) Patches of melting snow and ice,

   b) Puddles or rivulets of melt water on the ice.

   Young ice and lightly topographic winter ice will tend to retain individual puddles, while ice with very heavy topographical features lends itself more to the formation of rivulets or bands. On young or winter ice, puddles appear whitish or pale blue, becoming darker blue or green as they deepen. Shallow puddles appear much the same on polar ice, but with continued development, change to deep blue and then green. Puddles aid in the disintegration of ice since water absorbs more heat than the surrounding ice, thus speeding the melting process of the surrounding and underlying ice.

2) Thawing Holes in the Ice---The result of puddles melting completely through the ice surface. These holes appear to be the same color as sea water, and usually indicate a late stage of disintegration. However, ice can be heavily puddled and have many thaw holes, and yet be thick and strong. Location, type of ice, and season must be considered before the ice is termed "rotten."

3) Frozen Puddles---Puddles that have frozen. They usually reflect little sunlight, and give a frosted-glass appearance. Reflection of sunlight on melt water will help determine whether or not puddles are frozen or starting to freeze.

The continuous motion and stressing of the ice pack causes cracking and differential movement, which result in the creation of various types and sizes of water openings. These openings may remain free of ice cover if the air temperature is above the freezing point, but if temperatures are below freezing ice may begin to form very rapidly.

The development of thick ice requires a year or more if crushing and fracturing is not involved. Once the initial layer of new ice is formed it acts as an effective insulator and slows the rate of growth. The curves in Figure 6-8 show this effect. An open water feature will develop ice about 14 inches thick during 10 days of -30°F temperatures, but during the next 10 days under the same conditions will only increase in thickness to about 21 inches. This rate of growth is variable and depends not only on the air temperature, but also on the salinity and temperature of the water. The curves as shown give a reasonable approximation of the rate of growth. (References 8, 9 and 10)

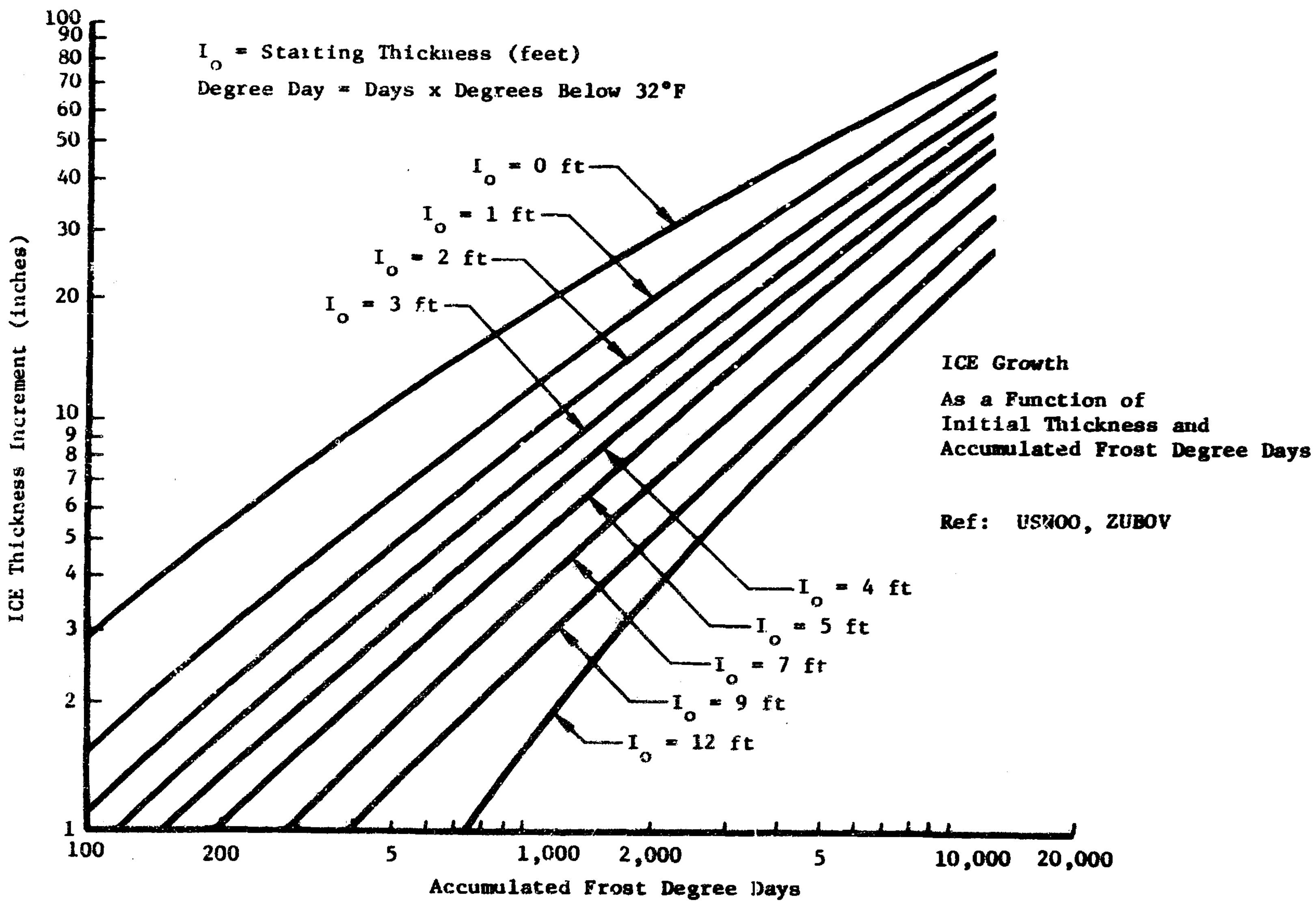

Figure 6-8: ICE GROWTH

Utilizing WMO-NAVOCEANO terminology, Table 6-2 gives the usual characteristic stages of ice development (Reference 10).

Table 6-2: CHARACTERISTIC STAGES OF ICE DEVELOPMENT

Type	Usual Age	Usual Thickness
New	Days to weeks	2 inches
Young	Days to weeks	2 to 6 inches
Medium	Days to weeks	6 to 12 inches
Thick winter	Weeks to months	12 inches
Young polar	1 to 2 years	7 feet
Arctic pack	2 years	8 feet

There is no reliable technique for obtaining extended synoptic and geographic ice thickness measurements; however, the type and age of the ice provides a crude but nevertheless usable method of determining the thickness of level ice. For this reason the data obtained by the Birds Eye flights which indicates the type of ice has been included. The primary limitation is the validity with which an airborne observer can determine the type and coverage. It is apparent that highly disturbed areas may contain many ice types as well as vertical relief from broken floes, and estimation is exceedingly difficult. The WMO reporting procedure requires only the reporting of the two most extensive forms of ice present in the spot observation and, in the case of similar concentrations, the older and thickest ice takes precedence. A result of this reporting procedure is reflected in the bar charts in that they seldom reach 100%. The presence of water openings also will reduce the value. An attempt to compensate for the latter has been made by incorporating a no-ice category to cover observations made off the edge of the pack. In general, however, it can be assumed that differences between the top of each bar and 100% consists of the younger and thinner forms of ice. Thicknesses by ice type neglect the effects of topographic relief.

The arctic pack, which is the oldest ice, is also the thickest ice. As might be expected the entire central portion of the ice pack is dominated by this form of ice. This is reflected in the data from the various sectors, which indicates that the center of this type is offset to the Pacific

side of the pole coincident with the permanent pack (Figures 6-3 to 6-6). As one moves out from the permanent pack, the percentage of arctic pack decreases and younger and thinner forms begin to cover a greater extent of the surface.

The thickness of the ice varies seasonally, thinning in the summer as a result of surface melting. A set of highly generalized curves showing seasonal ice thickness that can be expected as well as the sort of variations that occur along the North American coast are shown in Figure 6-9.

A plot of average ice drafts obtained during the Nautilus polar transit in 1957 shows that maximum drafts are found between 86° and about 88° on the Pacific side of the basin. The draft increases rapidly from the Bering Strait northweard to 86° and then shows a very general decrease from 88° to about 74° on the Atlantic side. The plot indicates an average maximum draft of about 20 feet, but this figure incorporates the much deeper keels that extend below the level ice surface (Reference 12).

The information on ice type is primarily useful as a measure of the probability of occurrence of ice of a given thickness, which may have an impact on whether sufficient strength is present to support a given load or the thickness is too great to permit a submarine to surface.

6.5.6 Water Openings

Water openings in the ice consist of any break or other discontinuity that exposes the underlying water. Depending on location and season, this underlying water may be open and unfrozen or it may be partially or completely covered with new or recently frozen ice. Floes may be present. The ice in a frozen opening will almost always be reasonably smooth on the upper surface and of less thickness than the surrounding pack. The openings are usually created through rupture of the pack and represent one of the results of the general pack dynamics. Even though these ruptures may refreeze they remain areas of weakness in the pack and as a result may be subject to repeated movement and rupture.

Water openings are of importance to vehicle operation both on the surface of the pack and under the pack. In the former case they represent another aspect of terrain relief and may or may not be an obstacle to movement depending on the thickness of the ice or lack of ice in the opening. To the submarine they represent the only access to the surface. A lack of openings effectively forces the submarine to remain submerged. Development of a technique to break thicker ice from below may, of course, alter this situation.

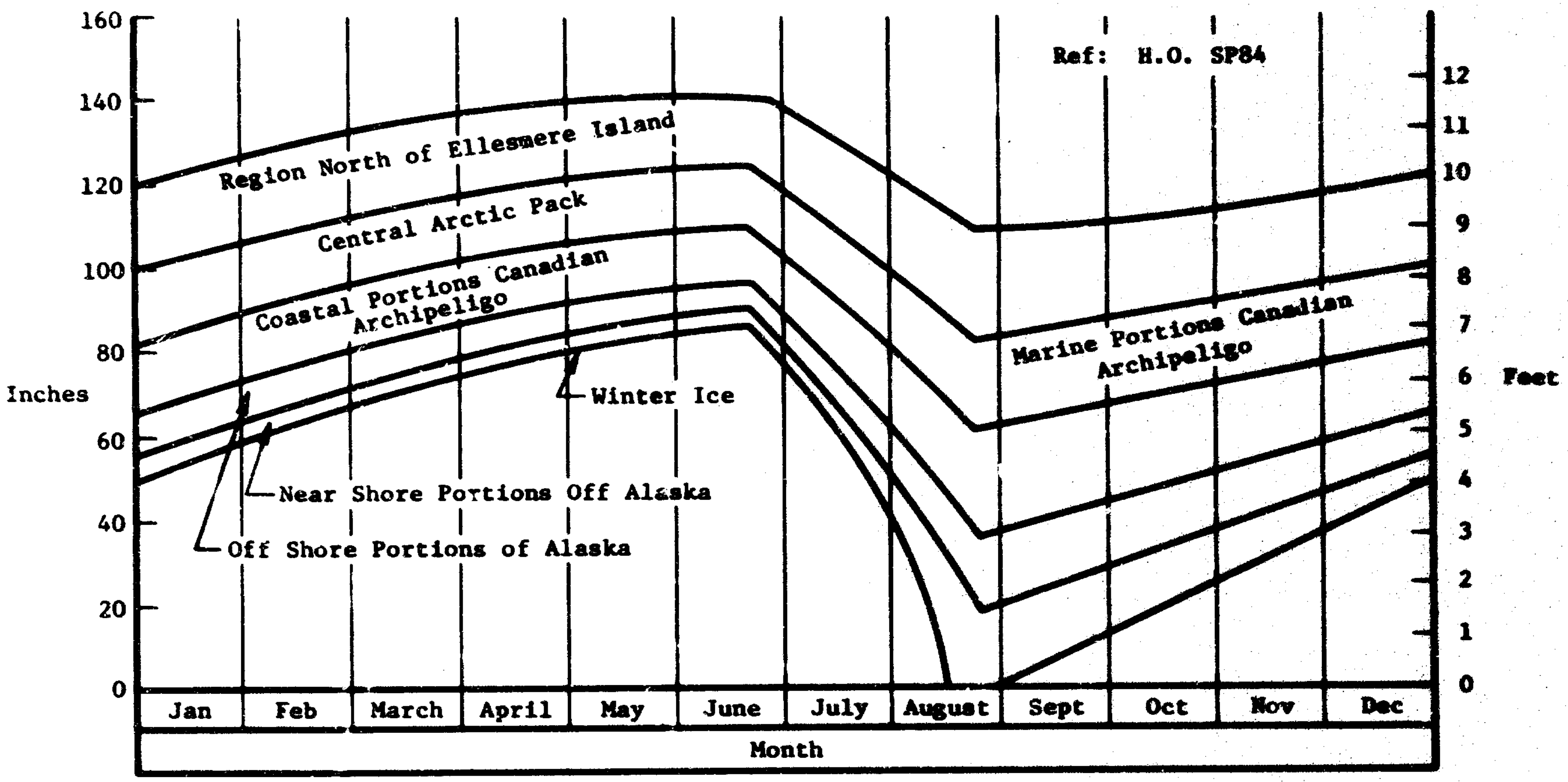

Figure 6-9: GENERALIZED ICE THICKNESS CURVES

The terminology applied to water openings, like much other ice terminology, is ill-defined; hence it is difficult (often impossible) to determine the size of reported openings unless additional information is supplied. Often, as in the Birds Eye data, terminology varies with the position of the observer and the observation technique used.

Water opening data is given in three formats in this report since three distinct types of observations are involved. The first and probably most reliable is the data obtained by the water opening observer on the Birds Eye flights. This data is obtained continuously while the aircraft is over the pack. The observer notes the time required to overfly a particular opening and, assuming a constant aircraft speed of 300 feet/second, determines the width of the opening as well as the orientation and ice cover in the opening. The openings are classified by this observer as:

Cracks	Any feature up to and including 150 feet in width;
Small	Any feature greater than 150 feet up to and including 600 feet in width;
Medium	Any feature greater than 600 feet, up to and including 1,500 feet in width;
Large	Any feature greater than 1,500 feet in width.

Water opening charts (Figures 6-10 to 6-13) were prepared for a random sampling of available Birds Eye flight reports. Since the time duration of the observation samples varied, the opening count was adjusted to a common base of 100 nautical miles and the summation taken of small, medium, and large openings. Cracks are reported separately because it is impossible to determine critical widths. Data is reported along the edges of the pack even though it is probably of slight significance due to close proximity to open water. It should be noted that there is no valid way to convert this data from a linear base to an area base since only overflight time is used in making the initial measurements. Other dimensions of the opening are unknown, and for that reason orientation data has not been considered.

The seasonal change in the number of water openings is evident, as are some of the major geographical variations such as those occurring along the coast of Alaska. It is of interest to note that the smaller number of openings in Sector B3A occurs near the central part of the Pacific Gyral.

The second form of water opening data is that given on the individual sector charts prepared from Birds Eye forward observer's reports. This information is considered less reliable than the

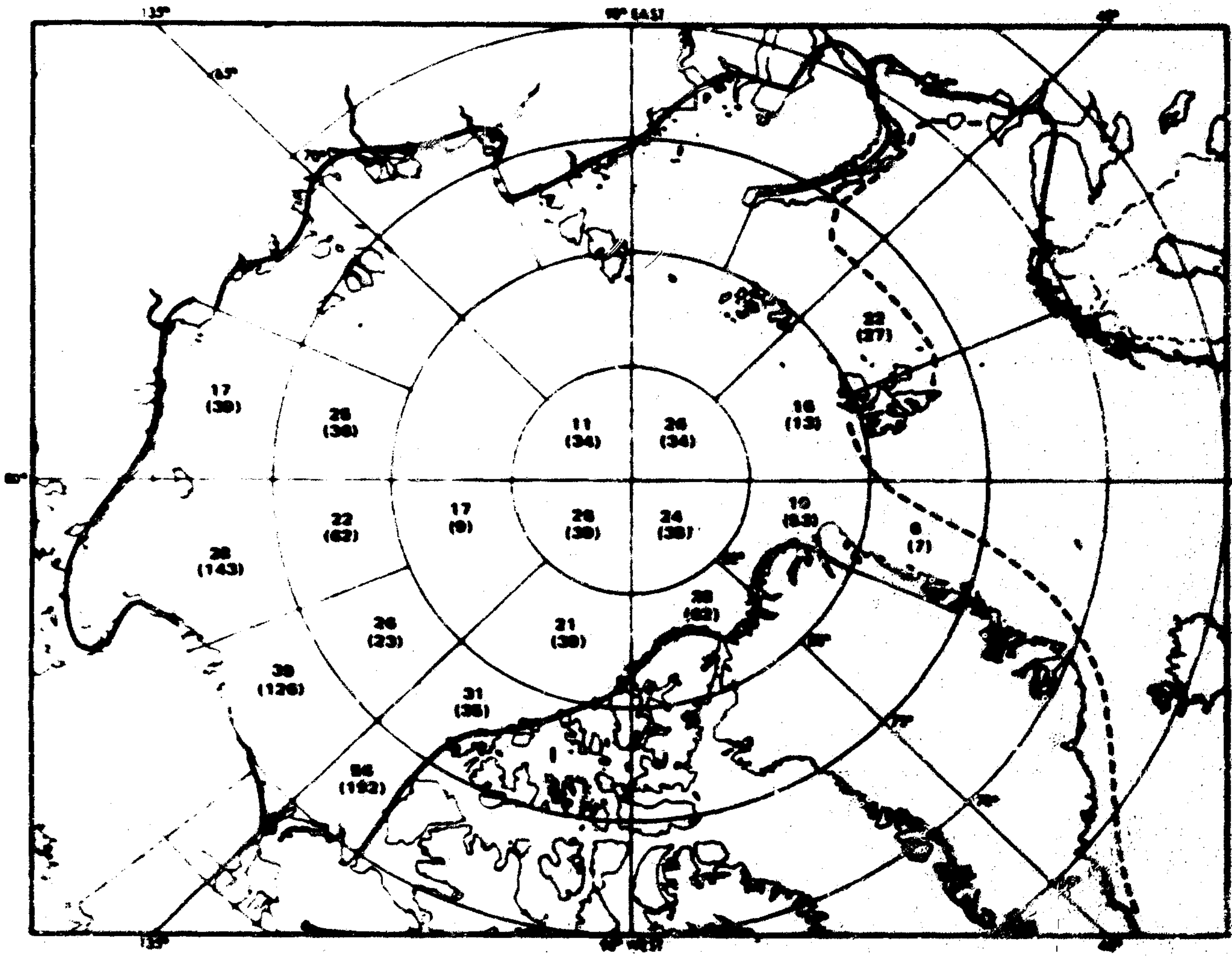

Figure 6-10: WATER OPENINGS WINTER

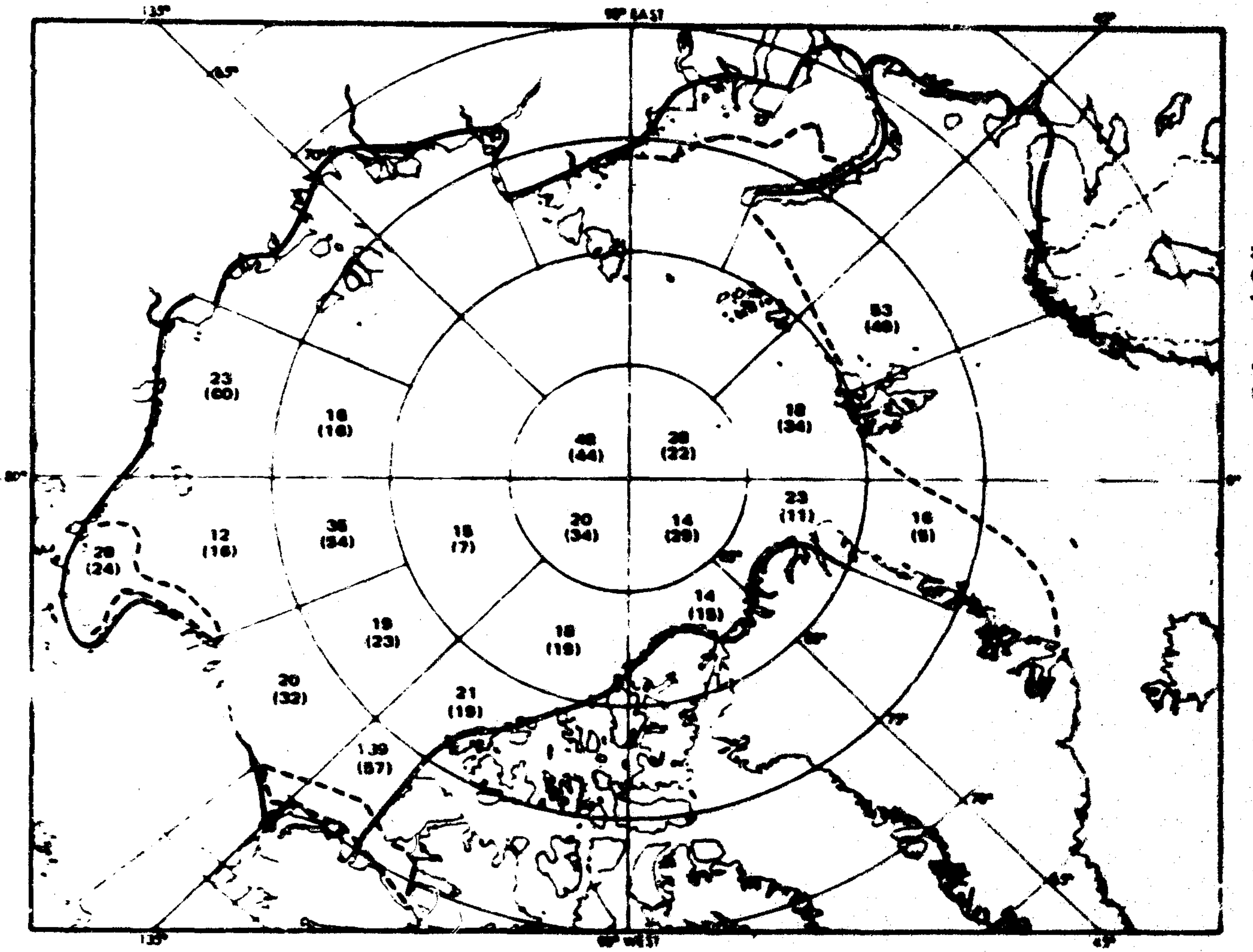

Figure 6-11: WATER OPENINGS SPRING

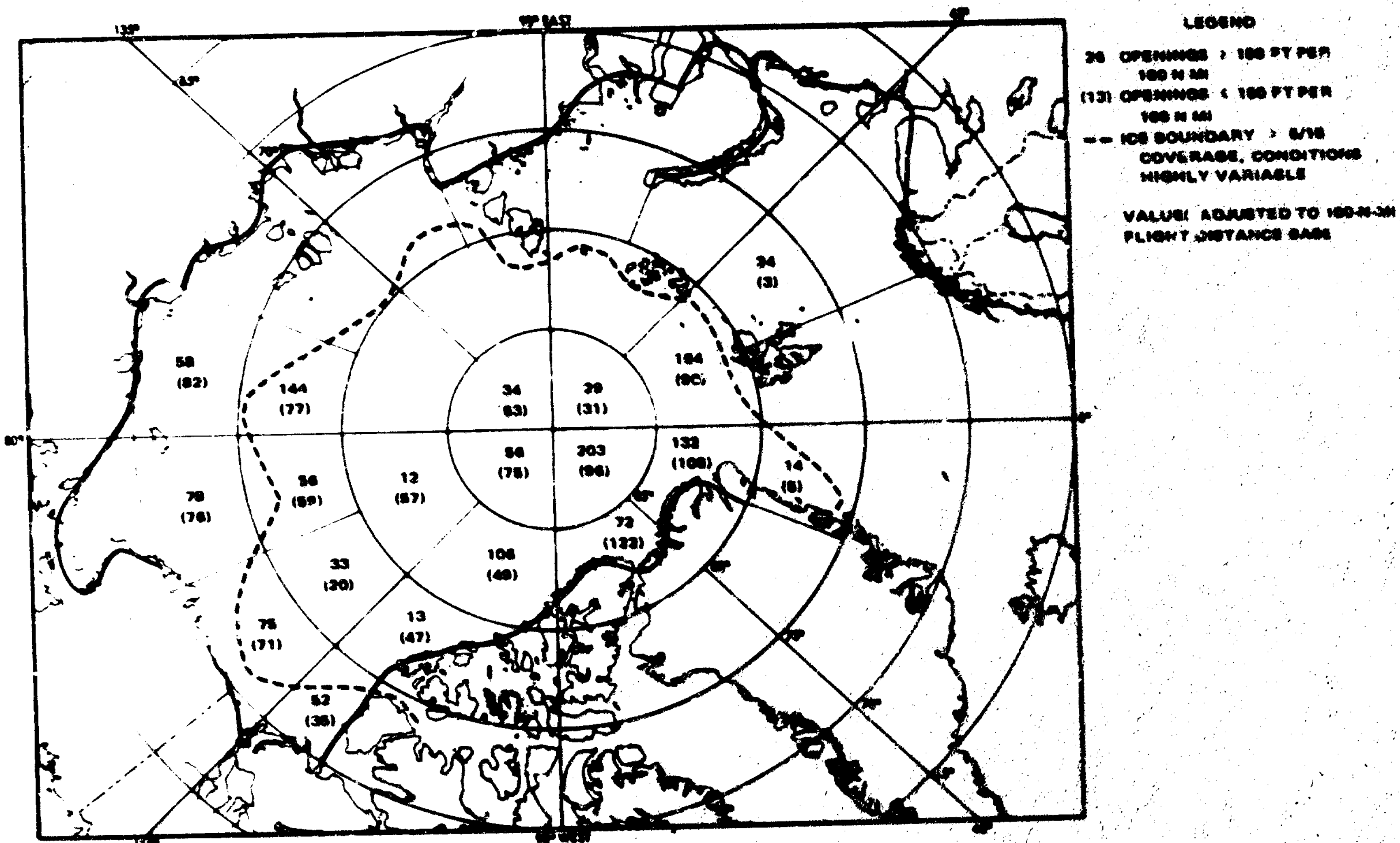

Figure 6-12: WATER OPENINGS SUMMER

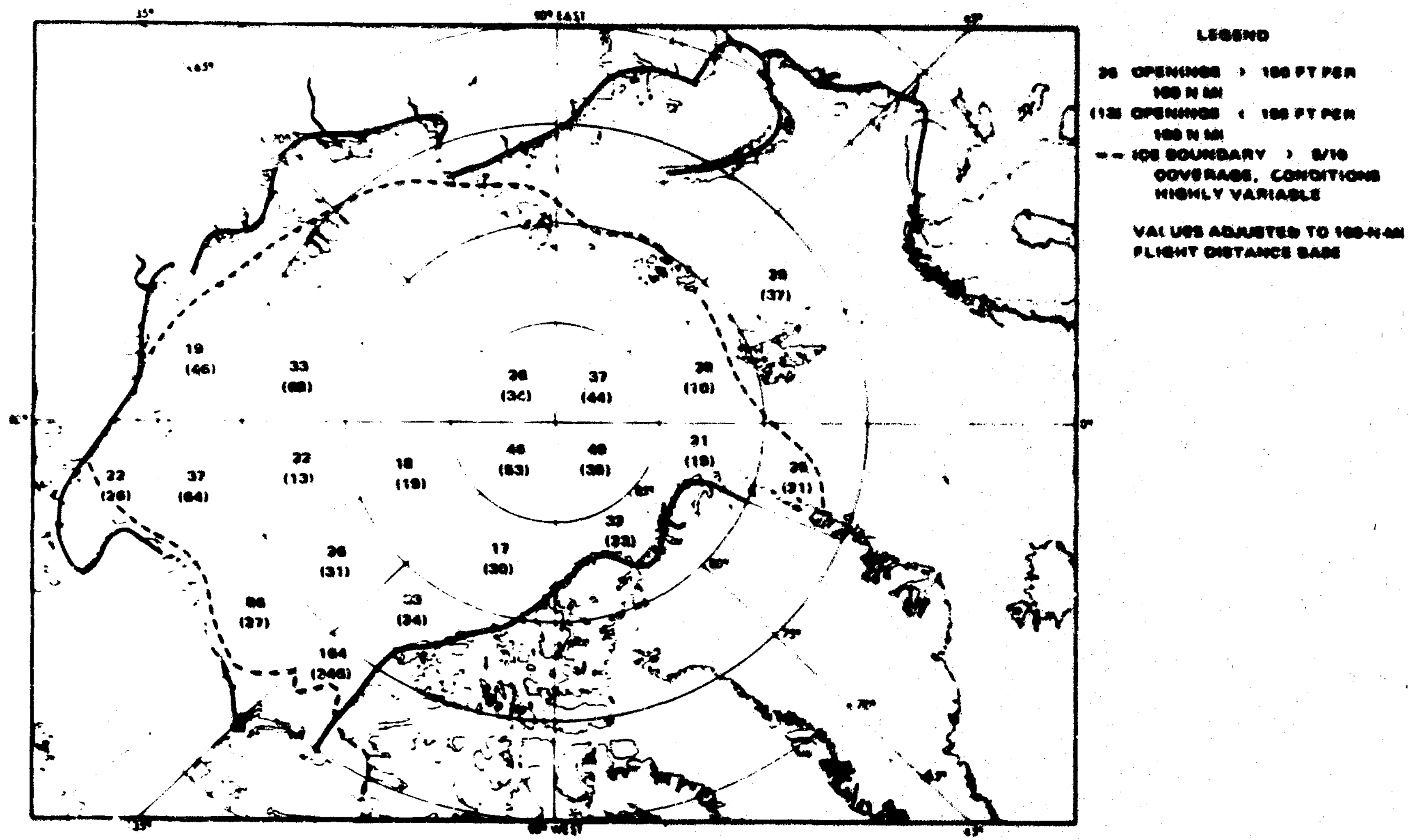

Figure 6-13: WATER OPENINGS FALL

preceding, but is included since it is area dependent. The problem with this data is in the ambiguity of the terminology that is reflected in both our own interpretation and the interpretation of the individual observer. The definitions given in the observer's manual are as follows:

1)	Crack	Any fracture of drift in sea ice not sufficiently wide to be described as a lead or lane;
2)	Polynya	Any sizeable sea-water area, other than a lead, encompassed by ice, greater than 1,000 feet across the major axis;
3)	Pool	Any enclosed, relatively small area of lesser concentration, 1,000 feet or less across the major axis;
4)	Lead/Lane	A navigable passage through pack ice or drift ice;
5)	Open water	Less than 1/10 ice concentration.

The no-ice line was added in the present tabulation to account for observations taken over open water away from the pack. To add further ambiguity, the reporting procedure given in the manual requires that the opening report give preference to the most significant openings present, utilizing the sequence as given above. The apparent polynya-pool transposition is evident.

The third form of water opening data given herein is that obtained from the two sets of submarine data available. This data is much more limited than that obtained from Birds Eye, yet in some sectors it is the only data available. For purposes of submarine operation, openings are considered to be ice thicknesses less than 4 feet determined on the basis of ice draft. One problem that should be noted with the submarine data is that the cruise tracks seem to be determined at least in part by the availability of so-called "friendly" ice. This is ice that has at least 10 openings per 30 nautical miles, thereby preventing or decreasing the likelihood of trouble should the submarine have to surface in an emergency.

Water openings from the submarine data are reported here as a percentage of measured track in each sector. No attempt has been made to adjust the values due to the sparsity of data.

6.5.7 Pack Ice Topography

The geomorphology of the pack ice is discussed briefly in Section 5.2.10. This section discusses the topography of the top and bottom of the pack and gives available data on the distribution of topographic features.

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Most of the relief found on the ice pack is the result of pressure action as the ice pack works under the force of winds and currents. In addition, however, terrain relief can result from melting of the ice and effects of erosion. The highest relief is found where pressure has caused the pack to rupture and pile.

The following topographic types can be distinguished:

Flat Ice	Ice that has formed free of any pressure effects. The surface is flat.
Rafted Ice	A type of pressure ice formed by one cake overriding another. Contours are well defined and can be considered recent.
Hummocked Ice	Ice piled haphazardly into mounds of hillocks. At the time of formation this ice is similar to rafted ice except that hummocked ice requires more pressure and heaping. After weathering no distinction is made.
Ridge	Pressure ice formed into a ridge that may be many miles long. May be highly curved along the long axis.
Sastrugi	Wave-like ridges of hard snow formed by wind action on a level surface.
Keel	The underwater projection associated with ridges and hummocks. Ridge is sometimes used if the meaning is evident.

(Reference 13)

The only direct measurements of the upper surface of the ice pack consist of the laser altimeter runs made by the Oceanographic Office. All other information is restricted to visual observation, the bulk of which consists of the data taken during the Birds Eye flights.

Birds Eye observers report topography in two forms. The WMO observer reports an estimated areal coverage of topography by type and the highest significant 1/3 of the features by making a division between great ridges (>10 feet), small ridges (<10 feet), great hummocks (>10 feet), and small hummocks (<10 feet). It is believed that these divisions are relatively meaningless since visual judgment of height from the air without adequate references is seriously open to question. However, the distinction between ridges and hummocks may be considered valid, and the height estimates are useful to the extent that the observer judged that a difference in height existed.

The ridge observer has a primary task of maintaining a ridge count and making ridge height estimates. It has been found, however, that this so-called ridge count is "every topographical feature

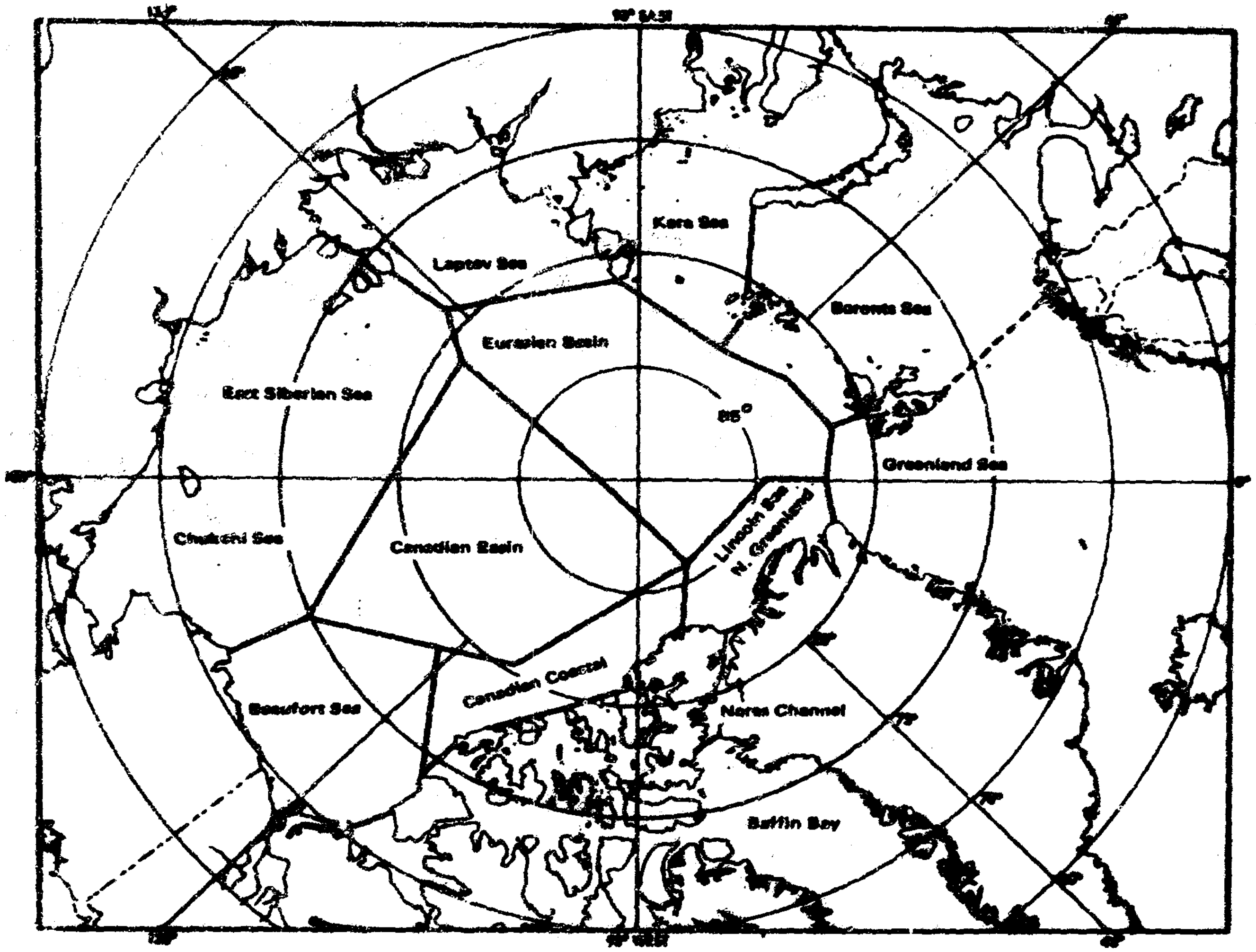
with discernible height in relation to the surrounding ice . . . with the exception of sastrugi." This count is, therefore, useful only as an indication of the extent of all kinds of relief present on the ice surface. Unfortunately, available Birds Eye reports do not include the height estimate data. The Birds Eye data compiled for this report does not include the count information since it is impossible to assess the significance of the count without the corresponding heights (Reference 2).

Ridge count and ridge height information for the Birds Eye flights made during 1962 and 1963 has been processed and reported on by Wittman and Schule. Because it is the only available summarized information on topography by count and height, the results are given here in Figures 6-14 to 6-21. It should be noted that the divisions used by Wittman and Schule are not directly correlatable with the sectors defined in this report. Perhaps the most significant conclusion to be drawn for this data is that the greatest number of topographic features are less than 12 feet in height. Furthermore, the counts are generally less than 20 to the mile.

It is impossible to assess the significance of the height estimates; yet because the topographic forms may be significant they have been included in the topography breakdown in each of the sectors. The only conclusions that can be made with the available information is that discernible topographic features cover from 20 to 35% of the pack north of 80°. There is little apparent seasonal variation. In the sectors on the Pacific side, the relief is somewhat less except in close proximity to the islands of the Canadian Archipelago where a definite increase occurs, probably as a result of the stresses induced into the ice from the eastward outflow through the islands. An increase in the area of topographic relief north of Greenland undoubtedly results from the effects of the Transpolar Drift. It has been noted that the Lincoln Sea has some of the roughest ice terrain to be found in the arctic.

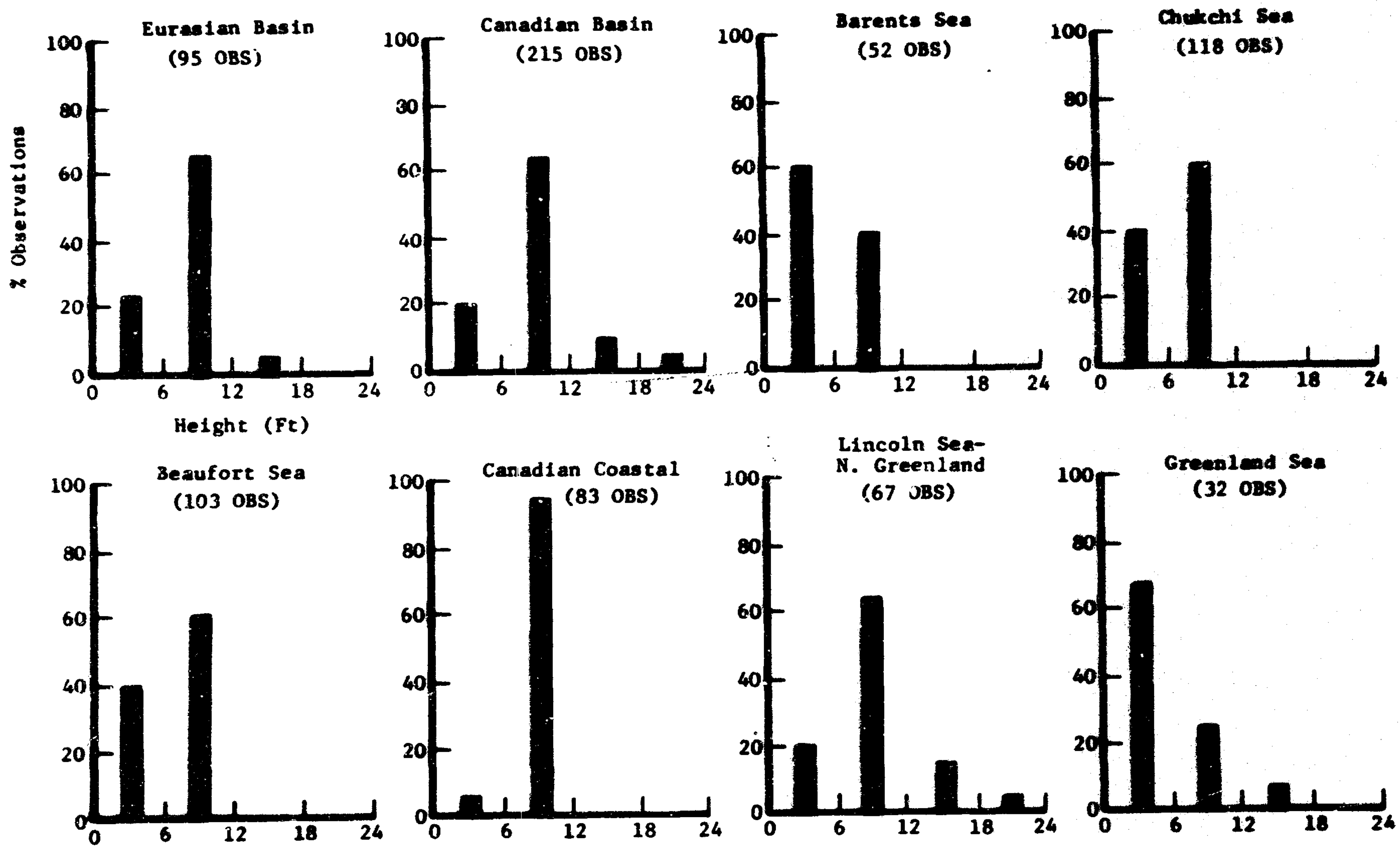
Information from the submarine data and visual description indicates that the underside of the ice pack is an extremely rough and variable surface with keels of considerable thickness, a few of which extend to over 100 feet below the ocean surface. The limited results available on keel depth are given on the submarine charts for each sector as well as in Figure 6-22, which show an average of conditions reported during the two seasons represented. It appears from these plots that the vast majority of the keels extend only 20 or 30 feet below sea level and that the deeper keels reported are exceptional.

It seems reasonable that the calculated heights and height distribution obtained from the submarine data could be applied to the Birds Eye data in the sectors where both sets of information are available, and that application to other sectors, while somewhat more questionable, would not be out of reason. This has not been done herein because other information is also desirable,



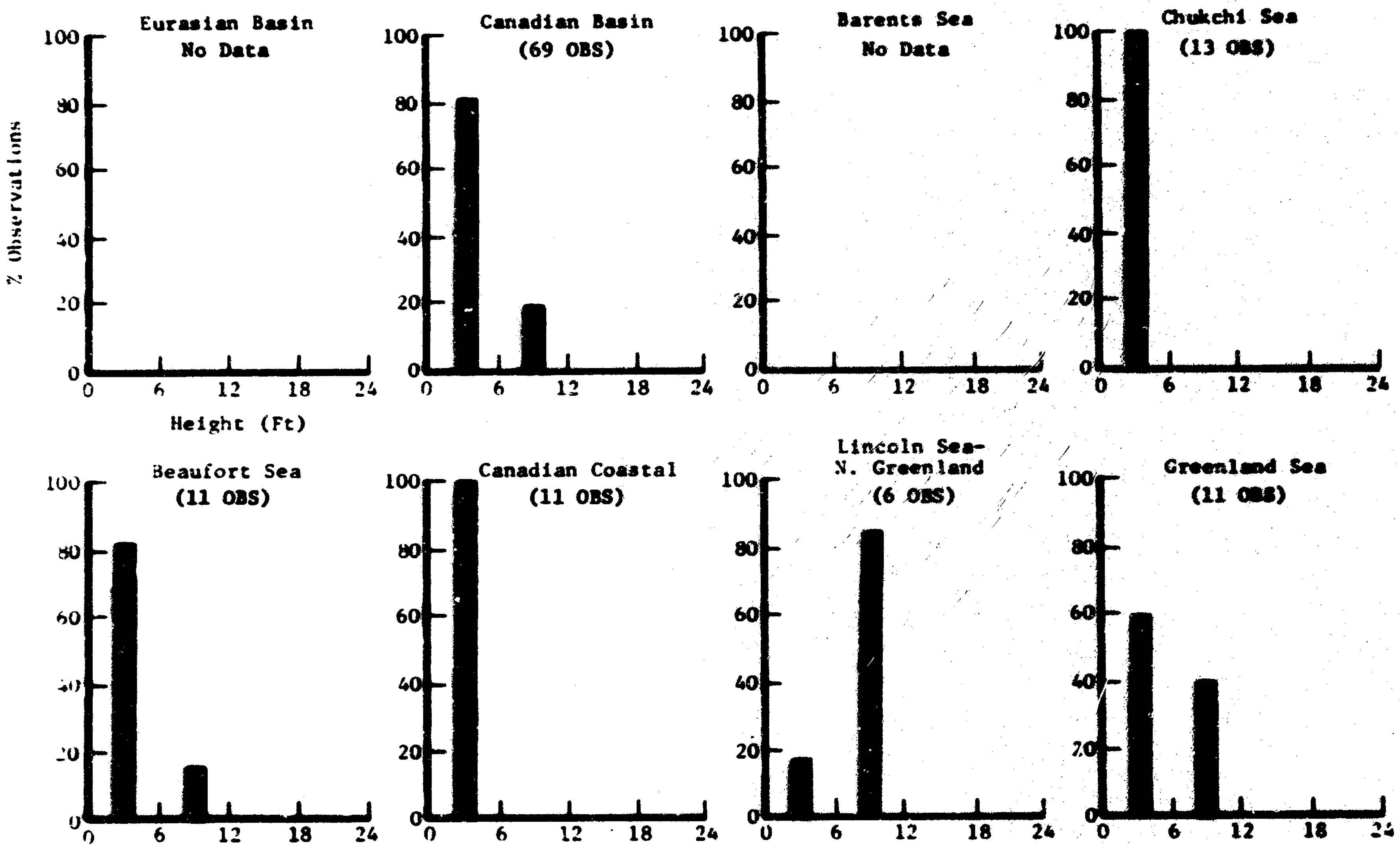
REF: WITTMAN & SCHULE 1967, IR 67-17 NOO

Figure 6-14: GEOGRAPHICAL DIVISIONS USED BY WITTMAN & SCHULE



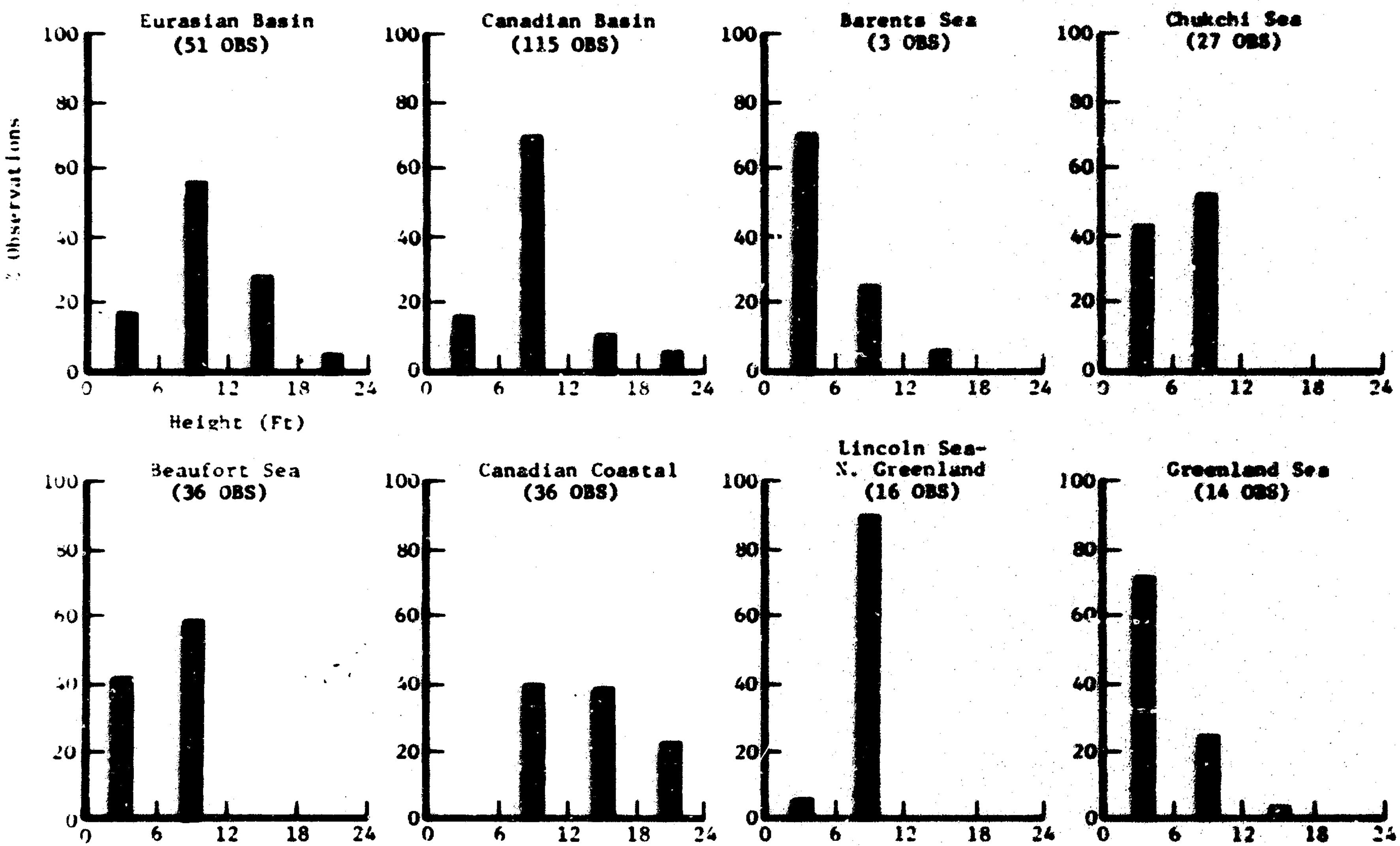
Ref: Wittman & Schule 1967, IR 67-17, NOO

Figure 6-15: SIGNIFICANT RIDGE HEIGHT
January-May



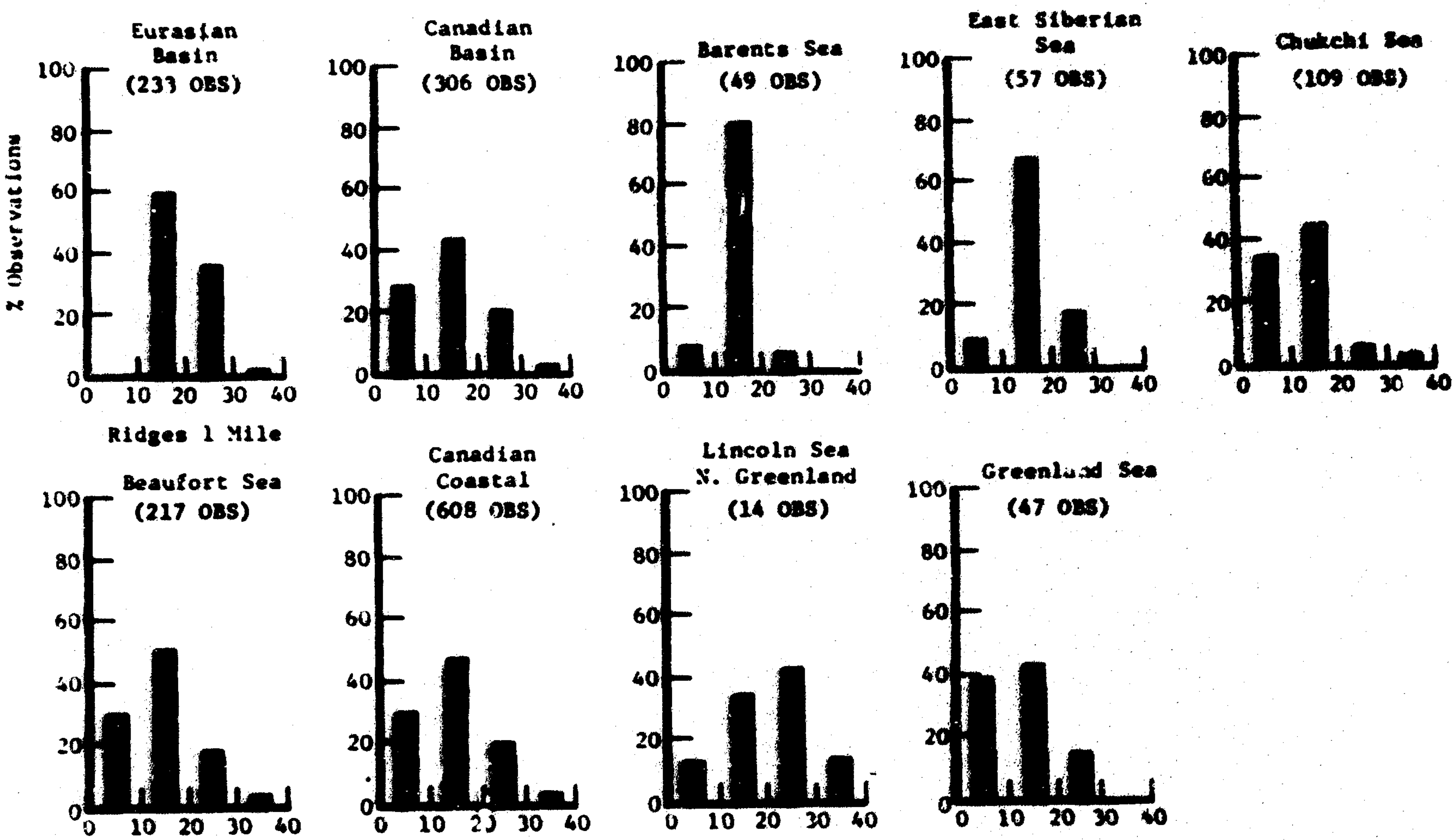
Ref: Wittman & Schule 1967, IR 67-17, NOO

Figure 6-16: SIGNIFICANT RIDGE HEIGHT
June-July



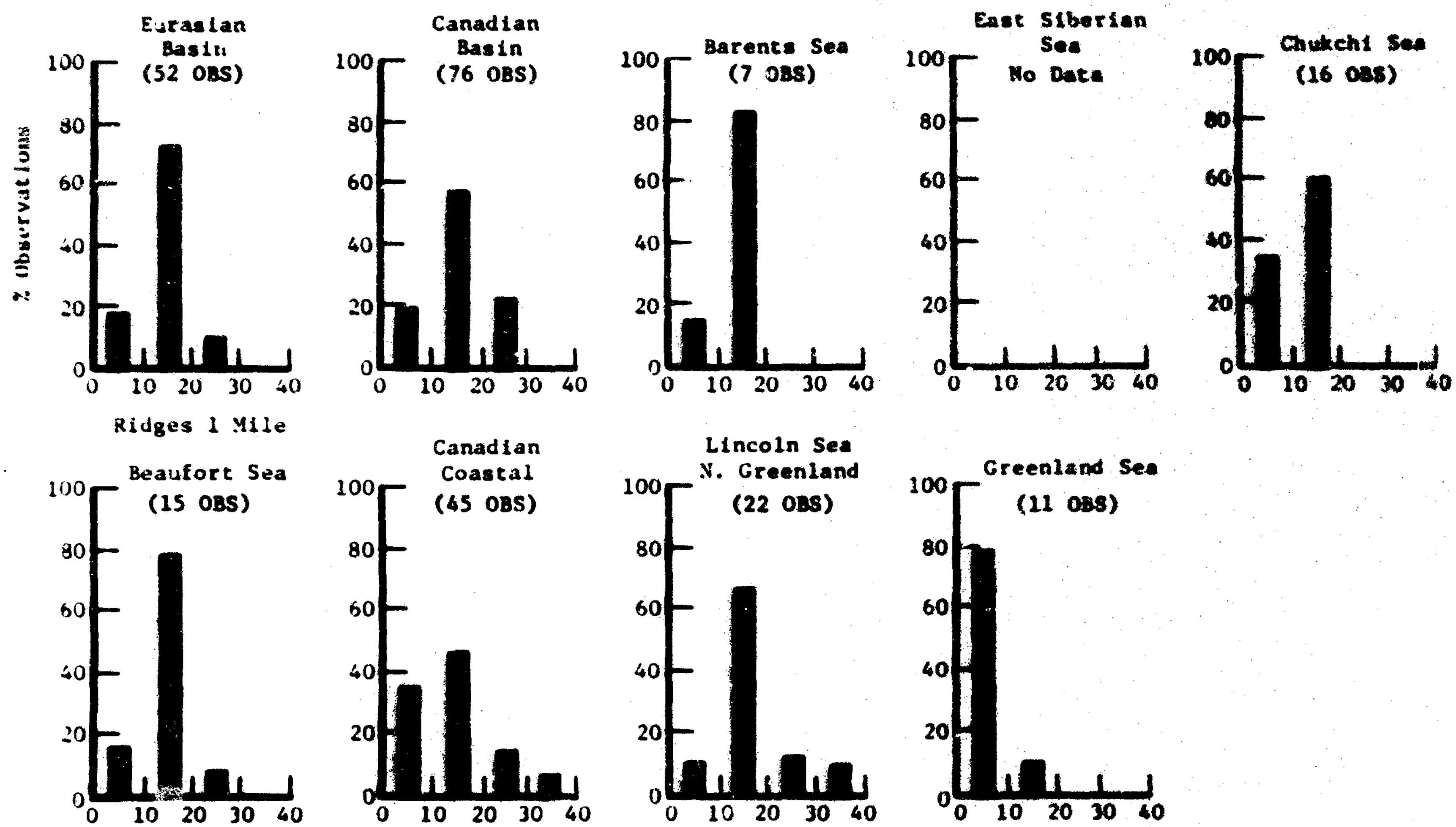
Ref: Wittman & Schule 1967, IR 67-17, NOO

Figure 6-17: SIGNIFICANT RIDGE HEIGHT
August-October



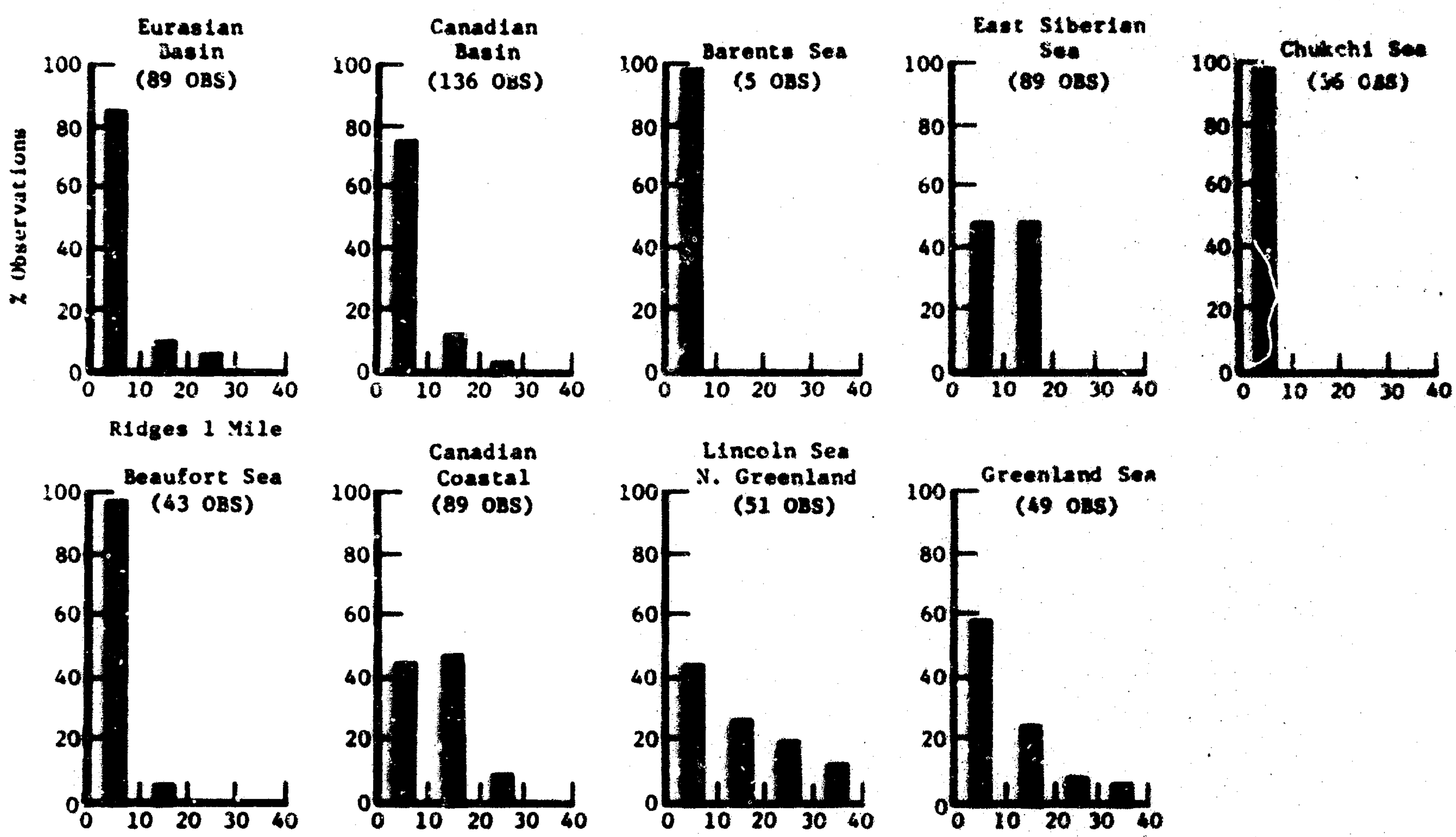
Ref: Wittman & Schule 1967, IR 67-17 NOD

Figure 6-18: RIDGE COUNT
January-May



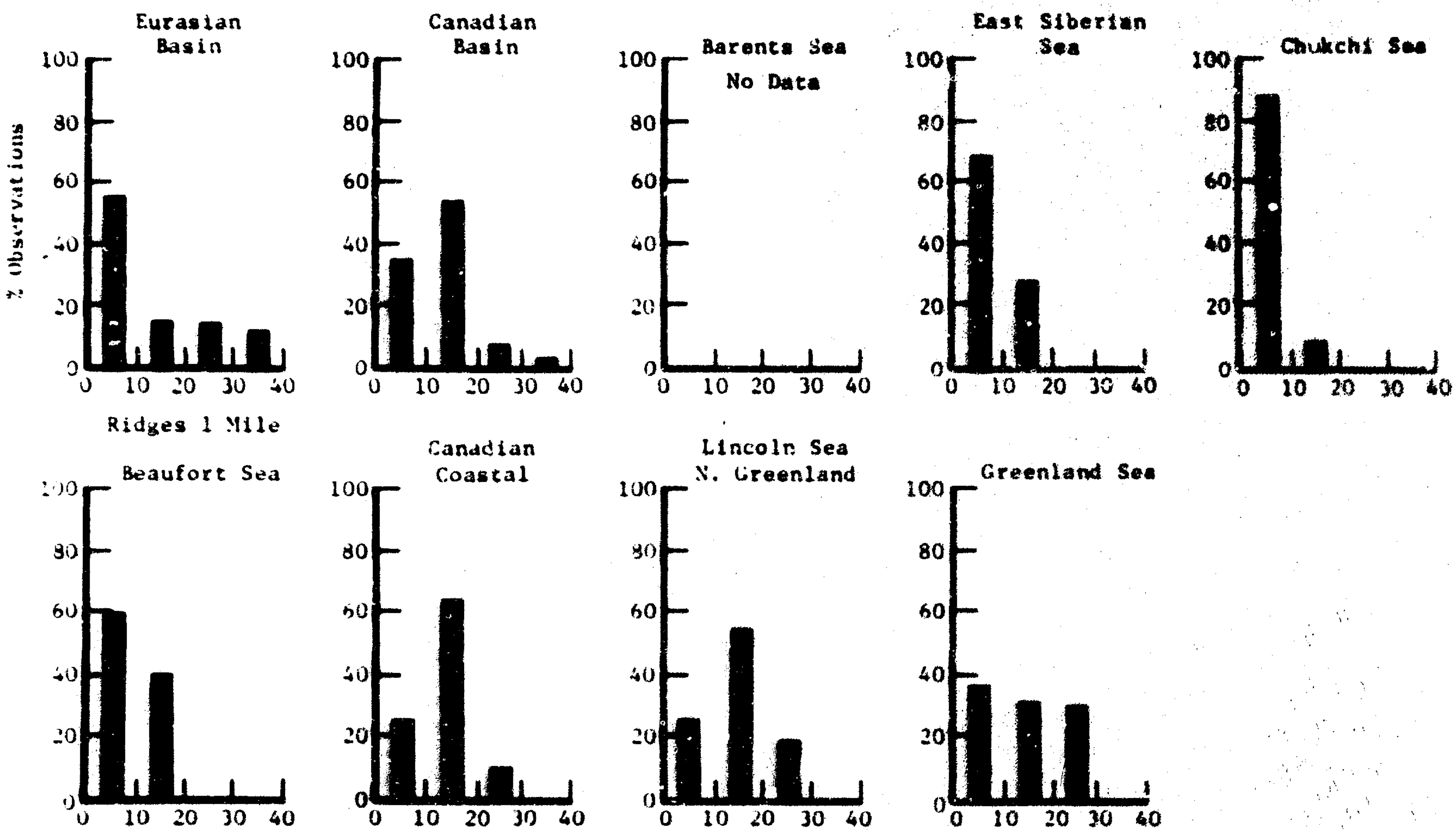
Ref: Wittman & Schule 1967, IR 67-17 NOD

Figure 6-19: RIDGE COUNT
June-July



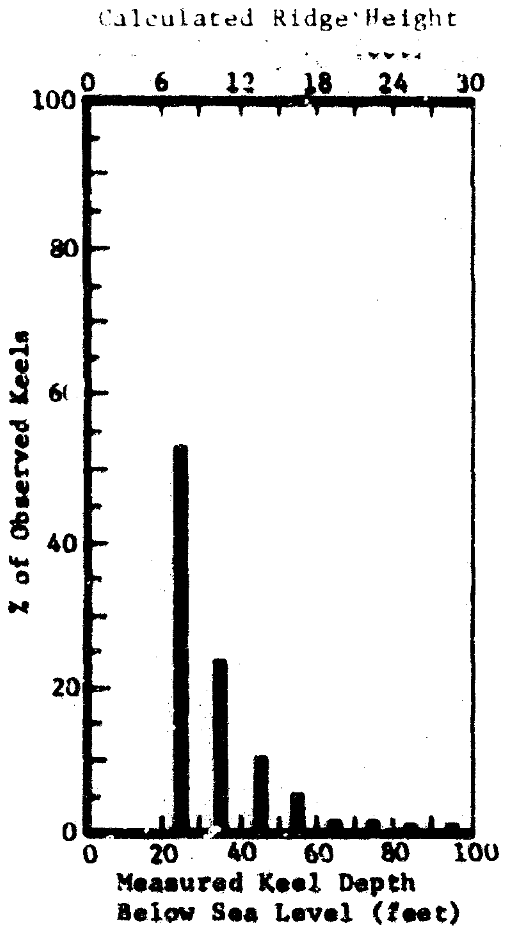
Ref: Wittman & Schule 1967, IR 67-17 NOD

Figure 6-20: RIDGE COUNT
August-October

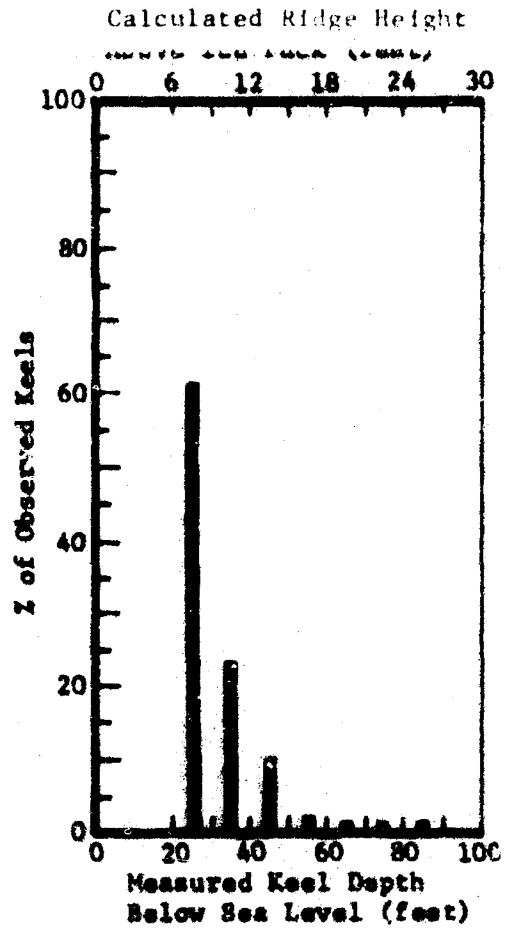


Ref: Wittman & Schule 1967, IR 67-17 NOD

Figure 6-21: RIDGE COUNT
November-December



WINTER



SUMMER

Observations	W	S
Track Segments	24	27
Total Length (n mi)	323	[illegible]

	W	S
Openings	2	13
Ice	98	87
Keels	21	14

% of Observed Track

Sectors A2, A3, B2A, B2B, B3A, B3B, C2C, C2D, C3C, D3A, D3B, E3A

Data Source: USS Sargo and USS Seadragon 1960

Figure 6-22: AVERAGE ICE CHARACTERISTICS, SARGO AND SEADRAGON CRUISES, 1960

including ridge and hummock distribution and spacing, lateral height distribution along a ridge, and height distribution as a function of ridge spacing.

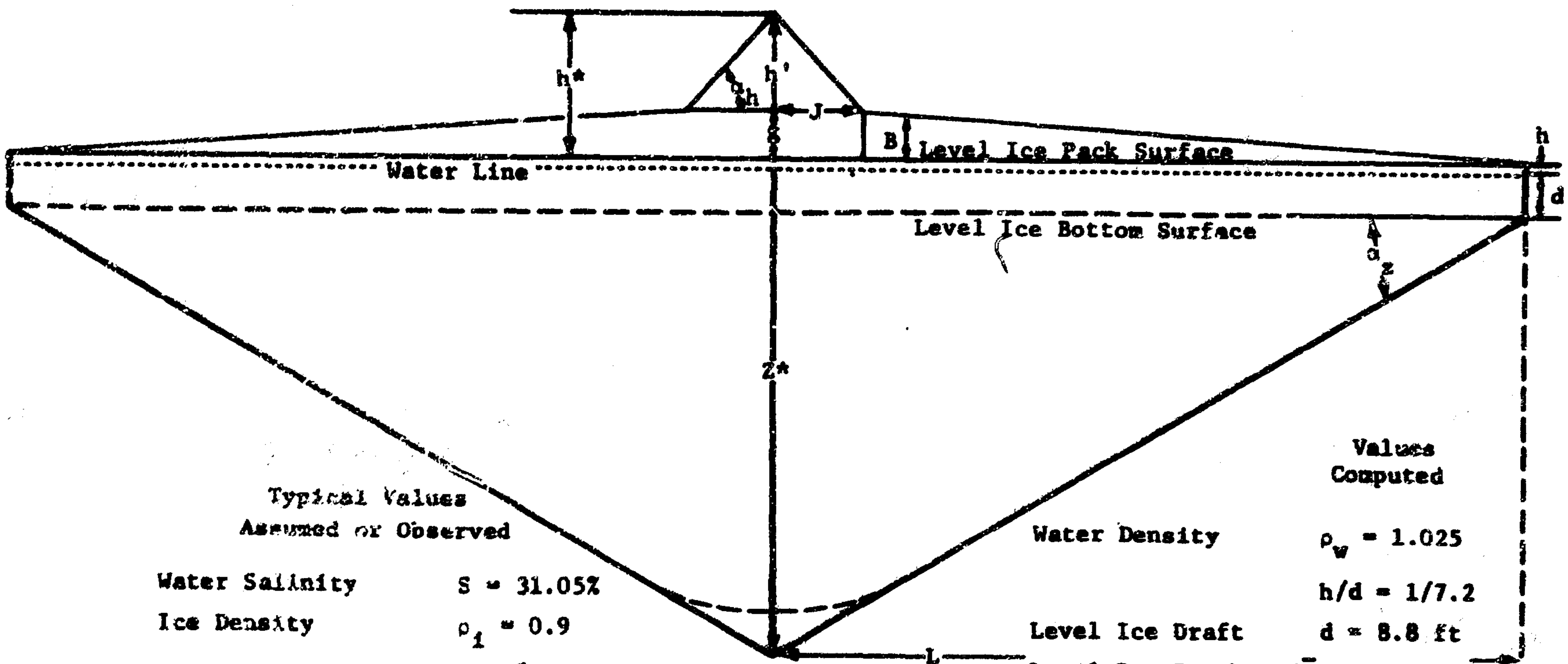
It has been established that the surface ridges and keels are parts of a common structural element in the ice. From the standpoint of maintenance of hydrostatic equilibrium this is not unexpected; the weight of any ice pile-up above the water surface ultimately must be compensated by a down-warping of sufficient ice to provide an equilibrium condition. Limited measurements have been made on height of ridges and depth of keels. From this information, a theoretical model has been constructed which is useful to calculate the dimensions of the entire structure. It is obvious that such a model must of necessity be simplified since it is impossible to account for all conditions which may be present in each individual situation. This model, termed the "Markov Model" (Figure 6-23) is not universally accepted, but it does provide a useful tool until more knowledge is available.

An additional scale on each submarine sheets shows a calculated ridge height value associated with measured keel information. There is some question as to whether the most important height is the ridge crest height or ridge height. The former is a term coined for use in this study and refers to the ridge height above the upwarped ice over the keel. The latter refers to the height of the ridge above a level ice surface. To be on the pessimistic side ridge height has been utilized and are based on a ratio 1/3.3 between ridge height and keel depth. (References 14 and 15)

During the winter cruise of the Sargo it was found that the average keel depth was about 33 feet, which would indicate an average ridge height of about 10 feet. During the Seadragon summer cruise the average keel was 30.14 feet giving an average ridge of 9.2 feet. These calculations show slightly higher ridges than the U. S. Navy Undersea Research and Development Center personnel observed while surfaced during a cruise. This group stated that the average ridge is about the height of a man, and that the highest ridge was 18 feet above sea level. Many other statements have been obtained to the effect that a man could see over most ridges.

There has no indication, either verbally or in reports, to substantiate statements that ridges may reach 100 feet in height, and it would appear that ridges above 15 feet are rare. The admittedly very limited laser run available indicates an average ridge and hummock height on the order of about 2 feet, although one ridge about 500 feet in length reached 12 feet.

On the basis of data in hand, it appears that the height of ridges has been generally exaggerated, and that the high points that have been measured and photographed are in fact only peaks occurring along a ridge line. It is evident that the ridge height problem, as well as other aspects of



Typical Values
Assumed or Observed

Water Salinity	$S = 31.05\%$
Ice Density	$\rho_i = 0.9$
	$h'/Z^* = 1/5$
	$\alpha_h = 50$ deg
	$\alpha_z = 32$ deg
Ridge Crest Height	$h' = 20$ ft
Keel Depth	$Z^* = 100$ ft
Ice Thickness	$h+d = 10$ ft

Values
Computed

Water Density	$\rho_w = 1.025$
	$h/d = 1/7.2$
Level Ice Draft	$d = 8.8$ ft
Level Ice Freeboard	$h = 1.2$ ft
1/2 Ridge Width	$L = 146$ ft
1/2 Crest Width	$J = 16.8$ ft
	$g = 9.4$ ft
	$B = 4.2$ deg
Ridge Height	$h^* = 30.5$ ft
	$h^*/Z^* = 1/3.3$

Figure 6-23: MARKOV MODEL---CROSS SECTION OF PRESSURE RIDGE

surface topography, cannot realistically be determined until representative portions of the surface of the ice have been photographed and topographic maps prepared (Reference 14).

6.6 REFERENCES

1) U. S. Naval Oceanographic Office (Various Years), Birds Eye informal reports.

2) U. S. Naval Oceanographic Office (1967), Manual of Ice Observing and Reporting Procedures.

3) Smith, A. N., R. Salaman, and J. Auterman (1963), Factors AFfecting Radio Communications From Beneath Sea Ice (C), Report No. 52-P-1, Vol. 2, DECO Electronics (AD 337 554) (C).

4) U. S. Naval Oceanographic Office (1968), Infrared Scanning the Arctic Pack Ice, IR No. 68-115.

5) U. S. Naval Oceanographic Office (1958), Oceanographic Atlas of the Polar Seas, Pt. II Arctic, HO 705.

6) Campbell, W. J. (1966), Sea-Ice Dynamics in Arctic Drifting Stations, Arctic Institute of North America.

7) Dunbar, M. and W. Wittman (1962), "Some Features of Ice Movement in the Arctic Basin," Proceedings of the Arctic Basin Symposium, October 1962, Arctic Institute of North America.

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9) Zubov, N. N. (1938), "On Maximum Thickness of Perennial Sea Ice," Meteorologiia i Gidrologiia, 4, No. 4.

10) Wittman, W. I. and G. P. MacDowell (1964), Manual of Short-Term Sea Ice Forecasting, U. S. Naval Oceanographic Office, SP-82.

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12) Lyon, W. (1961), "Ocean and Sea-Ice Research in the Arctic Ocean via Submarine," Transactions of the New York Academy of Sciences, Ser. II, Vol. 23, No. 8.

13) U. S. Navy Hydrographic Office (1952), A Functional Glossary of Ice Terminology, HO 609.

14) Wittman, W. I. and J. J. Schule (1967), Comments on the Mass Budget of Arctic Pack Ice, U. S. Naval Oceanographic Office, IR 67-17.

15) Skiles, F. L. and W. I. Wittman (1966), "Sea Ice Paramants Affecting Underice Operations," Proceedings of the Third U. S. Navy Symposium on Military Oceanography (C).

6.7 ARCTIC ICE PACK GLOSSARY

Crack — Any fracture that has not parted; in Birds Eye any opening less than 150 feet in width.

Drift — Motion of sea ice resulting from current.

Fast Ice — Ice that forms and remains attached to a shore, to an ice wall, to an ice front, between shoals, or to grounded ice bergs.

Fast Ice Boundary — The demarcation at any given time between fast ice and pack ice, or between areas of pack ice of different concentration (latter could also be "concentration boundary").

Floe — Any relatively flat piece of sea ice 60 feet or more across.

Fracture — Any break or rupture through very close pack ice, compact ice, compact pack ice, consolidated pack ice, fast ice, or a single floe resulting from deformation processes.

Friendly Ice — A submariner's term for an ice canopy containing many large areas of thin ice or other features which permit a submarine to surface. There must be more than ten such features per 30 nautical miles (56 km) along the submarine track.

Hummock — A hillock of broken ice forced upward by pressure. May be fresh or weathered. The submerged volume of broken ice under the hummock, forced downwards by pressure, is termed bummock.

Ice Island — A large piece of floating ice extending about 16 feet above sea level which has broken away from an ice shelf having a thickness of 100 to 160 feet and an area of about 20,000 square feet to 200 or more square miles, usually characterized by a regularly undulating surface that gives it a ribbed appearance from the air.

Ice Keel	A submariner's term for a downward projecting ridge on the underside of the ice canopy; the counterpart of a ridge. Ice keels may extend as much as 160 feet below sea level.
Ice Shelf	A floating sheet of considerable thickness showing 6 to 160 feet or more above sea level and attached to the coast. Usually of great horizontal extent and a level or greatly undulating surface. Nourished by annual accumulation and by the seaward extension of land glaciers. Limited areas may be aground. The seaward edge is termed an ice front.
Pack Ice	Any area of sea ice, other than fast ice, no matter what form it takes or how it is dispersed.
Shore Ice	Ice that has been cast onto the shore or beached as a result of the action of wind, waves, current, tide, or the force of an adjacent ice area.

7.0 ARCTIC CLIMATOLOGY

7.1 INTRODUCTION

Description of climatological conditions in the arctic region is proportional to the quantity and availability of the observations. The arctic ice pack is probably the least observed region on Earth, in terms of surface data. Scattered observing stations have been established for some time along the coasts of the surrounding continental land masses, and limited data has also come from polar expeditions. Not until the establishment of drifting research stations on ice islands has routine data on the central Arctic Basin become available. Numerous stations have been occupied since the Russian North Pole I station began in 1937, but none have existed longer nor provided as much data as has Fletcher's Ice Island, designated T-3. First manned in March 1952, this station has furnished reports throughout most of the intervening period to its present status as the only reporting ice station. Much has been written concerning this station and numerous reports issued on portions of selected research studies. Nowhere, however, is there a summary of the complete climatological data records, nor of the many other ice stations.

Because data from these stations are not organized nor readily available in summarized form, the present study has attempted to bring as much information together as could be done within a limited effort. Sources of information have come from technical publications, previous climatological descriptions, summarized data, and original records. From these, this section presents the primary climatological variables of temperature, cloudiness, winds, visibility, precipitation, and synoptic circulation over the central Arctic Basin. Each variable is discussed separately, although whenever interrelated effects are apparent, additional comments are presented. It is believed that the data presented represent as complete a climatology of central arctic conditions as is presently possible.

7.2 DATA SOURCES

Microfilm data records were obtained from the National Weather Records Center (NWRC), Asheville, North Carolina, for all of the available observations taken from United States drifting stations. This file of data is incomplete, most noticeably in that T-3 records from 1962 through 1964 are absent. As many of the numerous ice stations had only limited operation before abandonment, only the records of T-3 and Arlis II were considered in the present study. The lifetimes and tracks of these two stations covered sufficient portions of the central Arctic Basin to be especially pertinent to this analysis.

The Russian ice island program has been a continuing one since the North Pole 1 station was established, with more than 13 additional stations operated through 1965; however, data from these stations is incomplete and extremely difficult to obtain. Only North Pole 2 data records were available to this study. Although North Pole 2 lasted only 1 year and traveled over a course covered by both T-3 and Arlis II, it was included for a reliability comparison, as the time period was much earlier than that of the United States stations (Reference 1).

Since the ice stations are drifting in time, a problem is created in analyzing the data which is not found in data from fixed stations. The problem is to determine what quantitative variations are caused by temporal changes and what is cuased by spatial movements. This problem has been treated by considering each months' data as a fixed geographical station. Because of this problem it also was considered necessary to obtain additional data from surrounding fixed land stations which would be used to "tie" the arctic analyses together. Microfilm records and summaries were obtained from NWRC for 23 Soviet land stations and three Alaskan stations. Eight stations in northern Canada and 10 Greenland stations were extracted from the U. S. Naval Airfield Summary. Additional data of stations in Norway and Russia were taken from tabular data prepared by the British Meteorological Office. (References 2 and 3)

The location of all these stations is given in Figure 7-1. The positions of T-3, Arlis II, and NP-2 are presented for the midseasonal months: January, April, July, and October throughout their operational existence. In addition, dotted lines emanating from Eielson Air Force Base, Fairbanks, Alaska, towards the pole are the flight tracks of Air Force "Ptarmigan" weather reconnaissance flights. Comparative data on cloudiness were obtained from the latter. Tables 7-1 and 7-2 list station names corresponding to the numbered positions in Figure 7-1: longitude, elevation, period of record, and data source.

7.3 CLIMATOLOGICAL ANALYSES

7.3.1 Cloudiness

Figures 7-2 to 7-5 present the frequency of occurrence in percent of "clear" conditions for midseasonal months. Clear conditions are reported when total cloud amount is equal to or less than 3/10 sky coverage. Observations were averaged to obtain representative daily cloud amounts from which monthly frequencies were computed. For any single chart, about 12 ice station positions were available to establish the pattern of cloudiness over the central arctic. Isolines of equal frequency were drawn so as to best represent the ice station data in association with the perimeter stations.

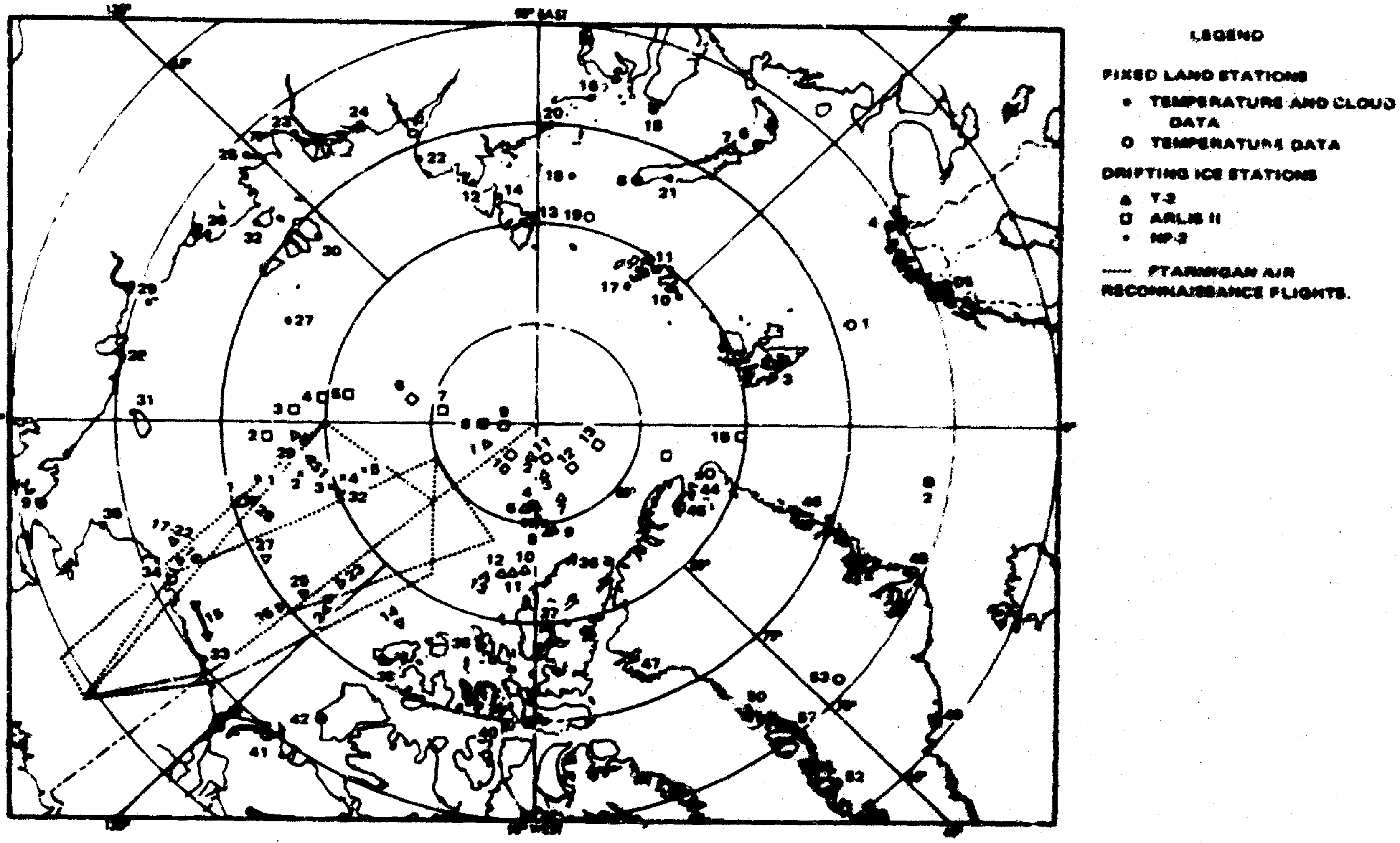


Figure 7-1: ARCTIC CLIMATOLOGICAL STATION LOCATIONS

TABLE 7-1: FIXED STATION POSITION LIST

Station	Latitude	Longitude	Elevation (feet)	Period of Record (years)	Reference	Position Number*
NORWAY						
Bjørnøya	74°31N	19°01E	49	10-25	a	1
Jan Mayen	71°01	8°28W	131	5-29	a	2
Grønfjorden	78°02	14°15E	23	19	a	3
Vardø	70°22	31°06E	43	49	a	4
Tromsø	69°39	18°57	335	47-60	a	5
USSR						
Malyye Karmakuly	72°23N	52°43E	49	17-29	a	6
Matochkin Shar	73°16	56°24	61	9	a	7
Cape Zhelanya	76°57	68°34	26	4	a	8
Velen	66°10	169°50	23	7	a	9
Aleksandry Zemlya	80°40	43°58	50	2	b	10
Bukhta Tikhaya	80°19	52°48	20	2	b	11
Mys Chelyuskin	77°43	104°17	43	11	b	12
Mys Golomyannyy	79°33	90°37	10	4	b	13
Mys Sverdlova	78°36	98°40	unknown	3	b	14
Ostrov Belyy	73°20	70°02	20	9	b	15
Ostrov Dikon	73°30	80°14	66	11	b	16
Ostrov Rudolfa	81°45	58°30	50	2	b	17
Ostrov Uedineniya	77°30	82°14	30	3	b	18
Ostrov Vize	79°30	76°59	59	3	b	19
Polar Station	75°24	88°40	unknown	3	b	20
Russkaya Gavan	76°14	63°34	26	7	b	21
Bukhta Pronchishchevoy	75°40	113°11	unknown	3	b	22
Bukhta Tiksi	71°35N	128°55E	26	11	b	23
Buolkalkh	72°56	119°50	unknown	3	b	24
Kazachye	70°45	136°13	72	9	b	25
Kosukhino	71°19	149°23	unknown	3	b	26

* See Position Diagram, Figure 7-1.

Table 7-1: (Continued)

Station	Latitude	Longitude	Elevation (feet)	Period of Record (years)	Reference	Position Number*
USSR (Cont'd)						
Mys Melville	77°07	156°35	unknown	2	b	27
Mys Shelagskiy	70°06	170°30	unknown	6	b	28
Ostrov Chetyrekhstolbovoy	70°38	162°24	20	4	b	29
Ostrov Kotelnyy	76°00	137°54	33	3	b	30
Ostrov Vrangelya	70°58	178°32	10	6	b	31
Mys Shelaurova	73°11	143°56	33	3	b	32
ALASKA						
Barter Island	70°08N	143°40W	21	8	b	33
Pt. Barrow	71°18	156°47	13	9	b	34
Cape Lisburne	68°52	166°08	52	5	b	35
CANADA						
Alert	82°31N	62°20W	95	9	c	36
Eureka	79°59	85°49	256	13	c	37
Isachsen	78°47	103°32	175	10-13	c	38
Mould Bay	76°14	119°18	40	12	c	39
Resolute	74°43	94°59	220	13	c	40
Nicholson	69°57	128°53	4	8	c	41
Sachs Harbour	71°57	124°44	270	2	d	42
Clyde	70°27	68°33	10	11-20	c	43
GREENLAND						
Nord	81°36	16°40W	118	8	c	44
Peary Land	82°10	30°30	29	2	c	45
Danmarkshavn	76°46	19°00	7	2	c	46
Thule AFB	76°31	68°44	251	12	c	47
Scoresbysund	70°29	21°58	56	12	c	48
Angmagssalik	65°36	37°33	95	30	c	49
Upernavik	72°47	56°07	59	40-48	c	50
Umanak	70°41	52°00	26	10	c	51
Sondrestrom	67°00	50°43	165	12	c	52
Eismitte	70°53	40°42	9843	1	c	53

* See Position Diagram, Figure 7-1

Table 7-1: (Continued)

References:

a. Tables of Temperature, Relative Humidity, and Precipitation for the World, Parts I, III, V, Meteorological Office, 617e, Air Ministry, London 1958.

b. Microfilm Records, N-type Standard Summaries, U.S. Weather Bureau, National Weather Records Center.

c. U.S. Naval Weather Service World-Wide Airfield Summaries, Vol. IV; Canada, Greenland, Iceland, November 1967.

d. Arctic Summary, Meteorological Branch, Department of Transportation, Toronto, Canada (6-Month Data Summary of Joint Arctic Stations).

Table 7-2: DRIFTING ICE STATION POSITION LIST

Station	Date		Latitude	Longitude	Position Number*
T-3	1952	April	87°34 N	156°30 W	1
		July	88°25	99°00	2
		Oct.	87°32	80°30	3
	1953	Jan.	85 58	91°10	4
		April	85°50	90°40	5
		July	85°44	95°40	6
		Oct.	86°10	71°40	7
	1954	Jan.	84°34	84°00	8
		April	84°40	81°30	9
	1955	July	82°44	93°34	10
	1957	July	82°30 **	97°30 **	11
		Oct.	82°20 **	101°30 **	12
	1958	Jan.	82°00 **	107°00 **	13
		Oct.	78°07	122°44	14
	1960	Jan.-Feb.	71°34	150°08	15
		April	71°40	157°15	16
		July	71°52	160°20	17
		Oct.	"	"	18
	1961	Jan.	"	"	19
		April	"	"	20
		July	"	"	21
		Oct.	"	"	22
	1965	Jan.	77°48	138°18	23
		April	76°48	137°34	24
		July	76°00 **	142°00 **	25
		Oct.	74°50 **	142°00 **	26
	1966	July	75°37	151°37	27
		Oct.	75°54	163°28	28
	1967	Jan.	78°35	177°03	29
		April	78°57	175°38	30
		July	79°04	170°08	31
		Oct.	80°05	159°09	32

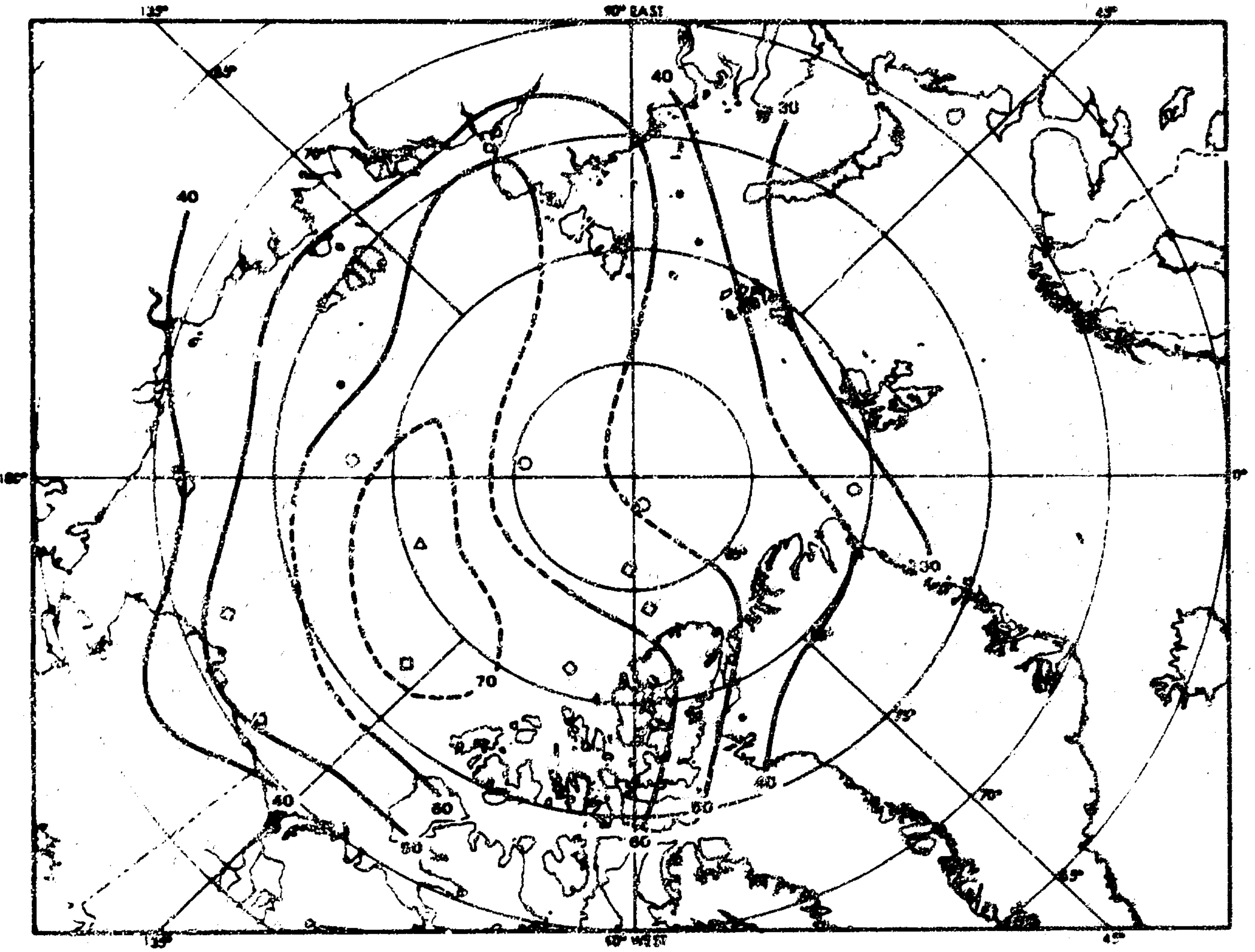
*See Position Diagram, Figure 7-1.
**Interpolated From Plotted Positions

Table 7-2: DRIFTING ICE STATION POSITION LIST (Continued)

Station	Date		Latitude	Longitude	Position Number*
Arlis II **	1961	July	75°30 N	163°00 W	1
		Oct.	77°15	177°00	2
	1962	Jan.	78°30	183°00	3
		April	79°45	187°00	4
		July	81°00	189°00	5
		Oct.	84°00	191°00	6
	1963	Jan.	85°30	188°00	7
		April	87°30	180°00	8
		July	88°30	179°00	9
		Oct.	88°00	130°00	10
	1964	Jan.	88°15	75°00	11
		April	87°15	50°00	12
		July	87°00	19°30	13
		Oct.	83°45	13°00	14
	1965	Jan.	80°15	3°00	15
NP-2	1950	April	76°27 N	192°37 E	1
		July	78°35	192°50	2
		Oct.	79°30	198°00	3
	1951	Jan.	80°34	197°18	4
		April	81°32	197°18	5

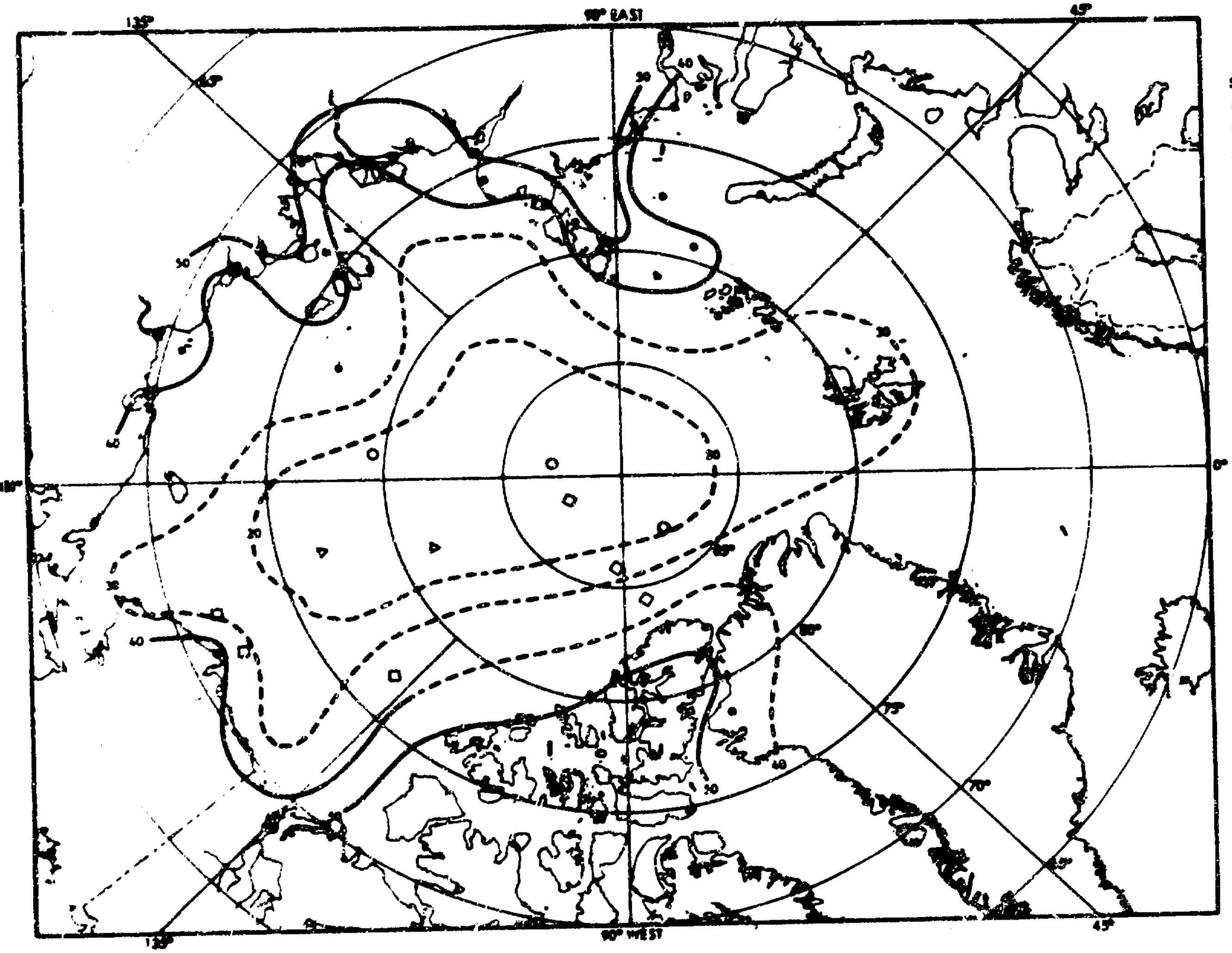
*See Position Diagram, Figure 7-1.

**Interpolated From Plotted Positions.



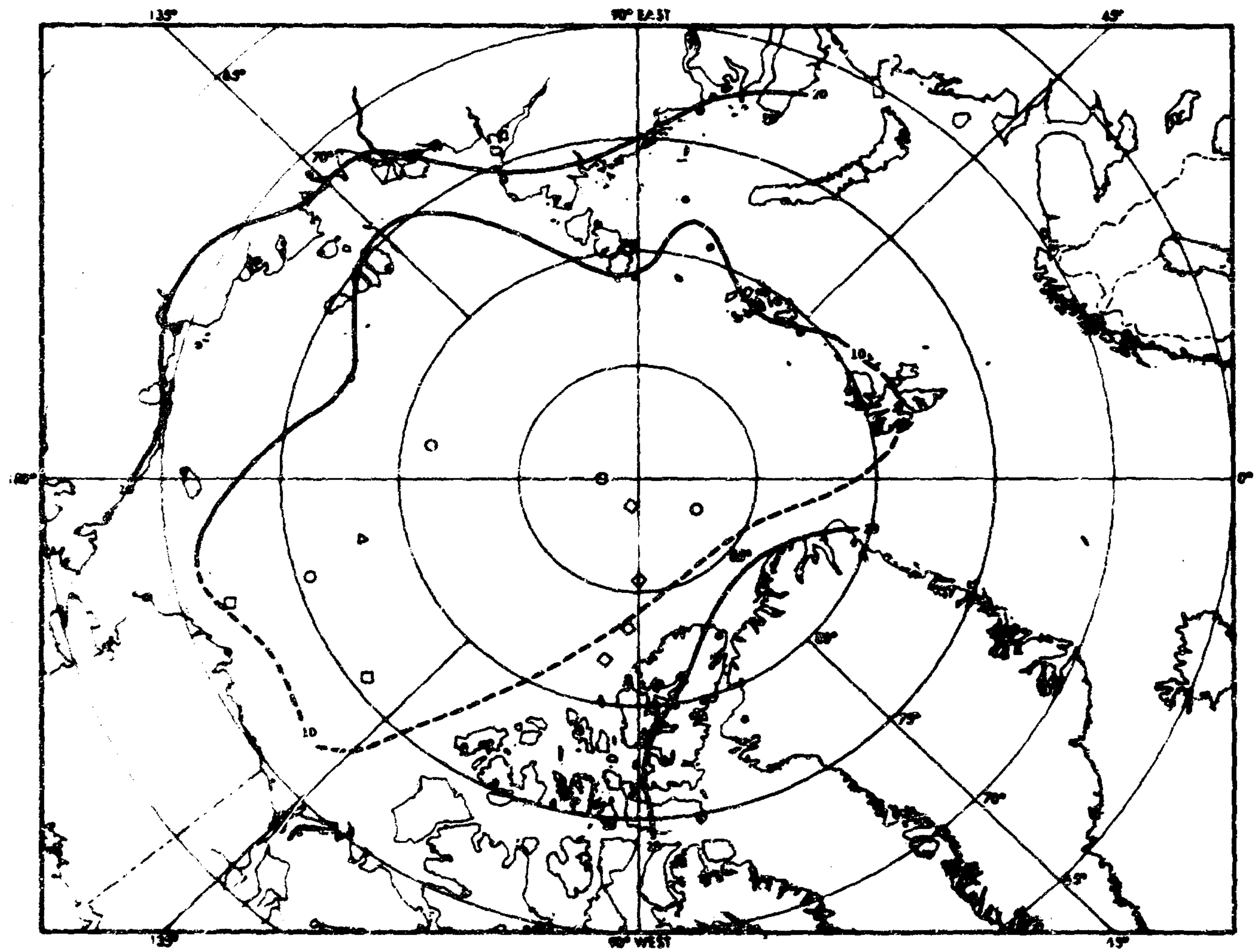
SOLID LINES BASED ON DATA FROM FIXED STATIONS. DASHED LINES BASED ON DRIFTING STATIONS AND AIR RECONNAISANCE FLIGHT DATA, AND IS LESS RELIABLE IN TERMS OF PERIOD OF RECORD.

Figure 7-2: TOTAL CLOUD AMOUNT PERCENTAGE FREQUENCY CLEAR (≤3/10) JANUARY



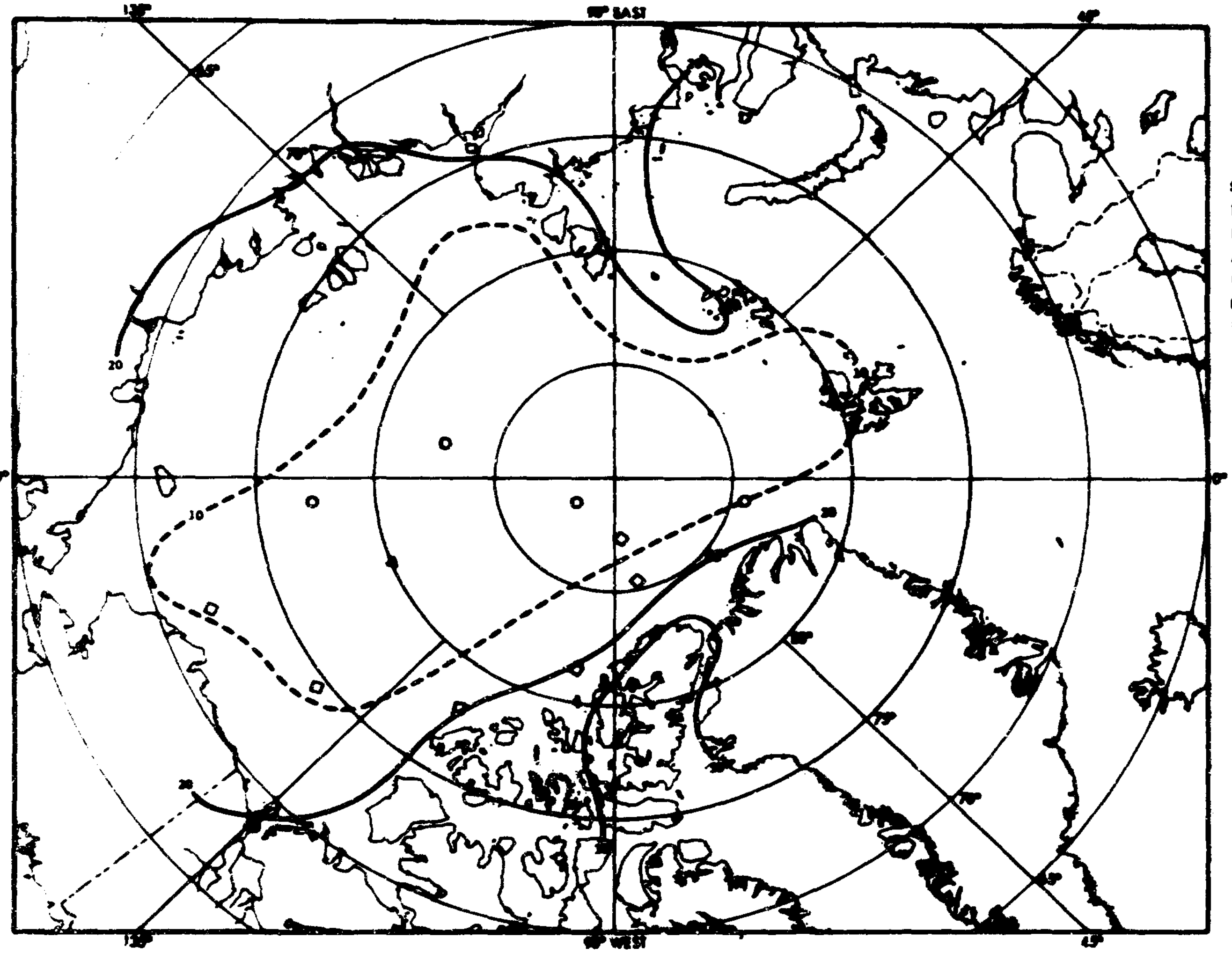
SOLID LINES BASED ON DATA FROM FIXED STATIONS. DASHED LINES BASED ON DRIFTING STATIONS AND AIR RECONNAISANCE FLIGHT DATA, AND IS LESS RELIABLE IN TERMS OF PERIOD OF RECORD.

Figure 7-3: TOTAL CLOUD AMOUNT PERCENTAGE FREQUENCY CLEAR ($\leq$3/10) APRIL



SOLID LINES BASED ON DATA FROM FIXED STATIONS. DASHED LINES BASED ON DRIFTING STATIONS AND AIR RECONNAISANCE FLIGHT DATA, AND IS LESS RELIABLE IN TERMS OF PERIOD OF RECORD.

Figure 7-4: TOTAL CLOUD AMOUNT PERCENTAGE FREQUENCY CLEAR ($\leq$3/10) JULY



SOLID LINES BASED ON DATA FROM FIXED STATIONS. DASHED LINES BASED ON DRIFTING STATIONS AND AIR RECONNAISANCE FLIGHT DATA, AND IS LESS RELIABLE IN TERMS OF PERIOD OF RECORD.

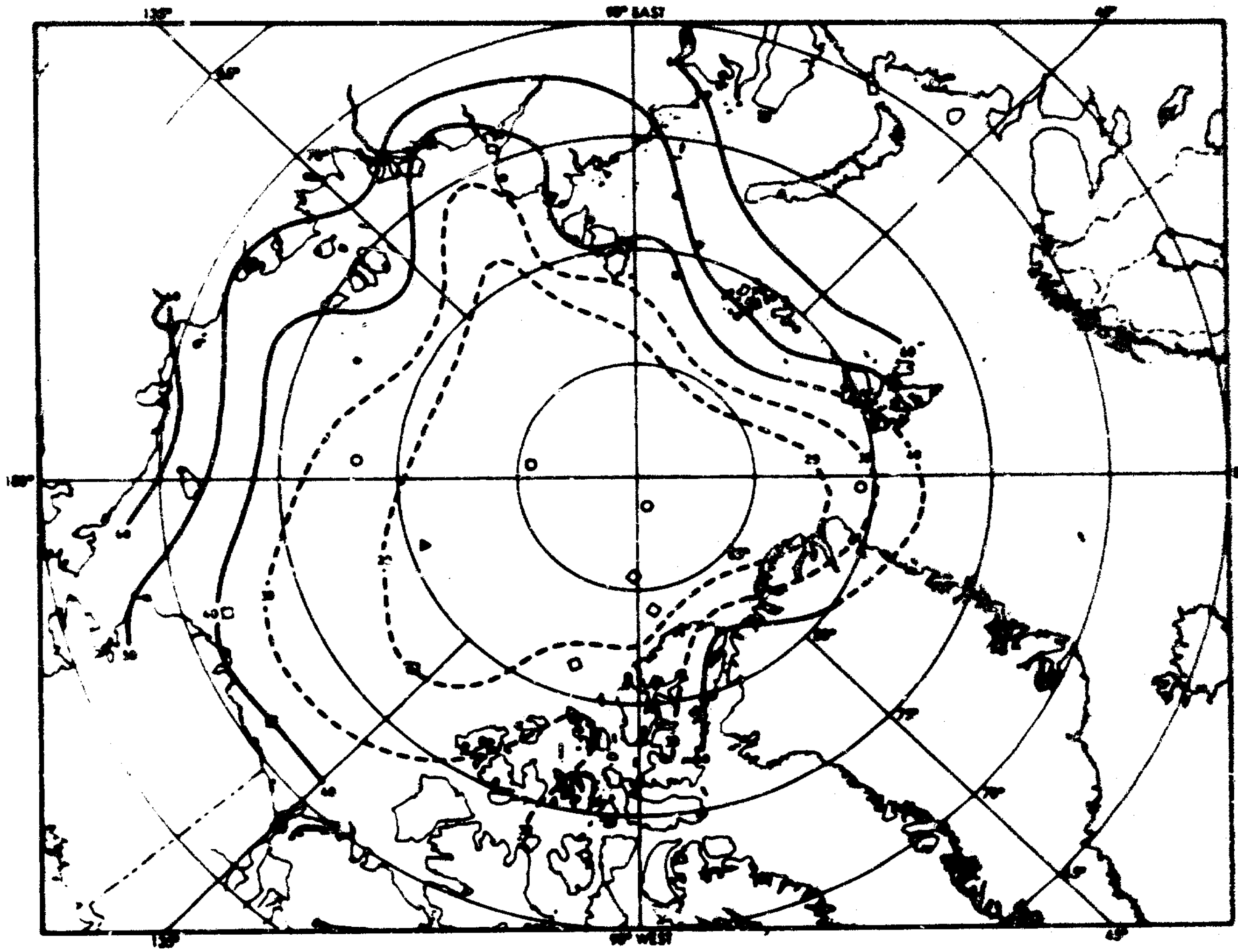
Figure 7-5: TOTAL CLOUD AMOUNT PERCENTAGE FREQUENCY CLEAR ($\leq$3/10) OCTOBER

It is observed that a high frequency of clear skies (>70%) occurs at 80°N, north of Point Barrow in January. The dominance of clear skies during the dark winter months has been noted by others. The percentage of clear skies drops sharply to April (<20%), and amounts to less than 10% of the observations during July and October.

The comparable frequencies of cloudy skies determined by sky cover ≥7/10 are shown in Figures 7-6 through 7-9. Less than 20% of January observations are for cloudy skies through the central arctic. The April pattern differs considerably from January, showing an area of large frequency of high cloudiness north of Wrangel Island. The July situation confirms the analyses of others, indicating a maximum of cloudy skies 90% of the time over the central arctic. A large frequency of occurrence of cloudy skies remains through October, although it appears to be shifted toward the Russian arctic.

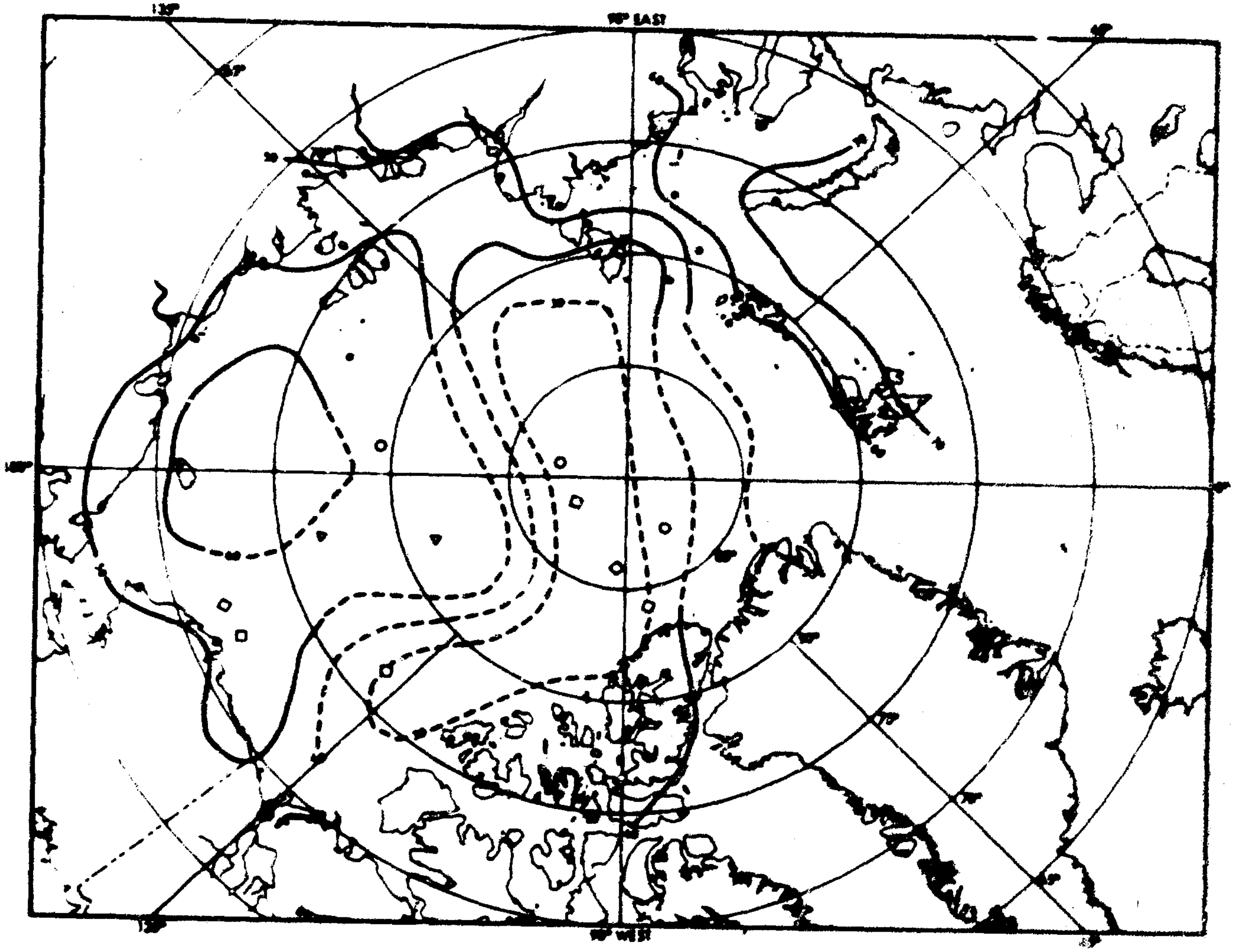
The annual cycle of cloud amount for observations from T-3 and NP-2 is presented in Figure 7-10. As many as 9 months (October) have been averaged in producing the T-3 distribution. The NP-2 curve is based on 1 year's observations and shows surprising agreement with the T-3 averages. Because of the similarity of these distributions, it is assumed that Figure 7-10 represents the annual course of cloudiness for the western half of the ice pack. Four high-latitude, fixed land stations are plotted in Figure 7-11, which shows cloudiness distribution in other parts of the central arctic. Comparison of Figure 7-11 with Figure 7-10 shows that the three Russian stations are similar to the ice island cloudiness during the May-to-October period. During the remaining months, there is a greater percentage of partial cloudiness (4 to 5/10) for the fixed stations. The cloudiness distribution for Alert is considerably different than any of the other stations depicted. A greater frequency of clear skies is noted in all months except January. Thus, the high winter clear frequency observed in the western ice region appears to be unique and of relatively short duration.

The almost continuous cloud cover of the arctic for the months of May to October is essentially one of low stratus- and occasionally altostratus-type clouds. As a result of an extensive flight research study of clouds by Russian observers, information on the frequency of cloud types, base height, top height and vertical thicknesses for summer months are presented in Tables 7-3 to 7-5. Observations over a 7-year period (1949-1955) support the fact that few clouds of large vertical development (cumulus and cumulonimbus) occur over the central arctic. From Table 7-4 it is apparent that the bases of stratus clouds were observed in the lowest 600 meters in 88% of the cases. Stratus tops in the 200 to 1,000 meter level occurred 75% of the time. The limited vertical depth of the summer stratiform cloudiness is consistent with many reported observations appearing in the literature. Clouds of greatest vertifal thickness in the arctic are nimbostratus averaging more than 1,000 meters deep (Reference 4).



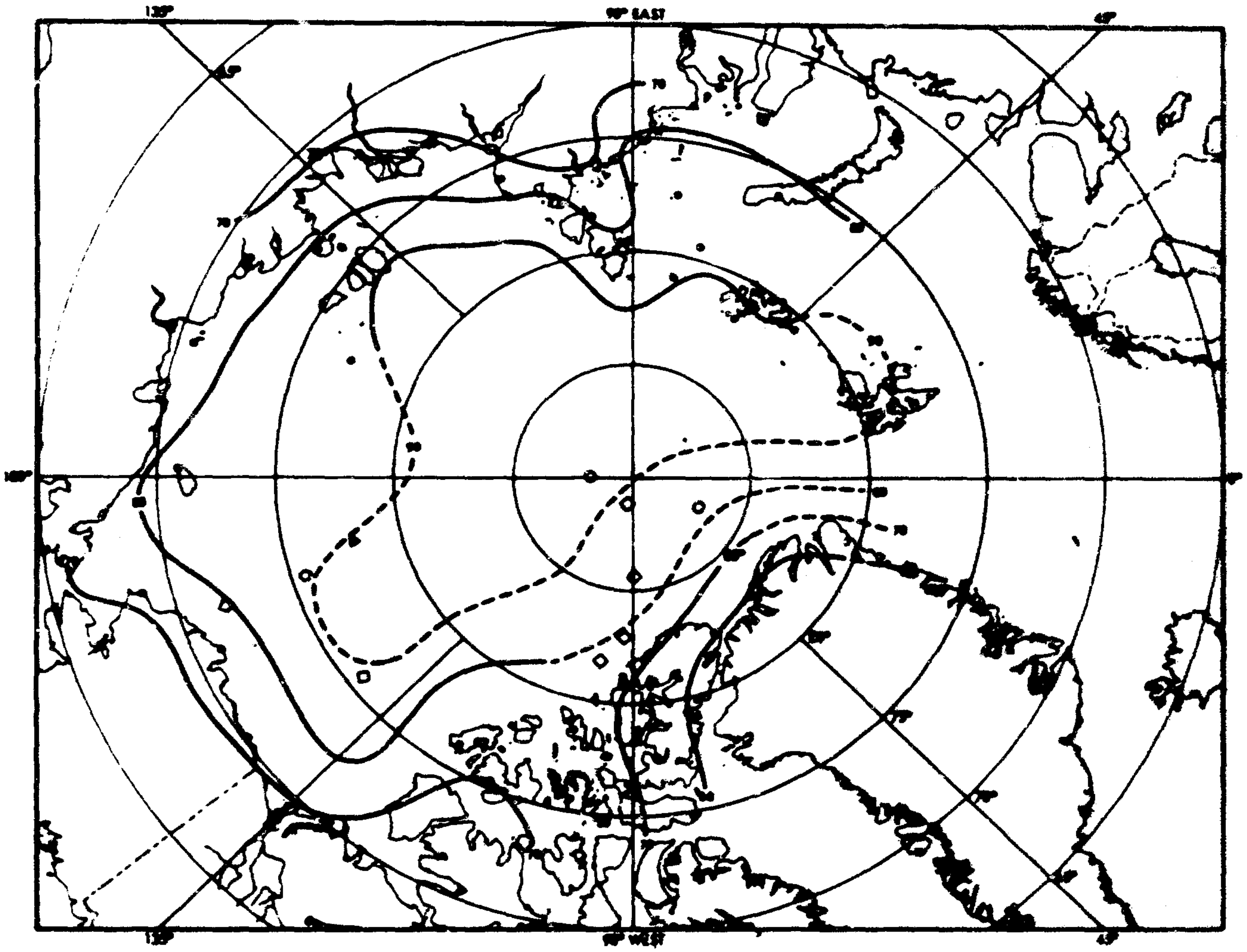
SOLID LINES BASED ON DATA FROM FIXED STATIONS, DASHED LINES BASED ON DRIFTING STATIONS AND AIR RECONNAISANCE FLIGHT DATA, AND IS LESS RELIABLE IN TERMS OF PERIOD OF RECORD.

Figure 7-6: TOTAL CLOUD AMOUNT PERCENTAGE FREQUENCY CLOUDY ($\leq$7/10) JANUARY



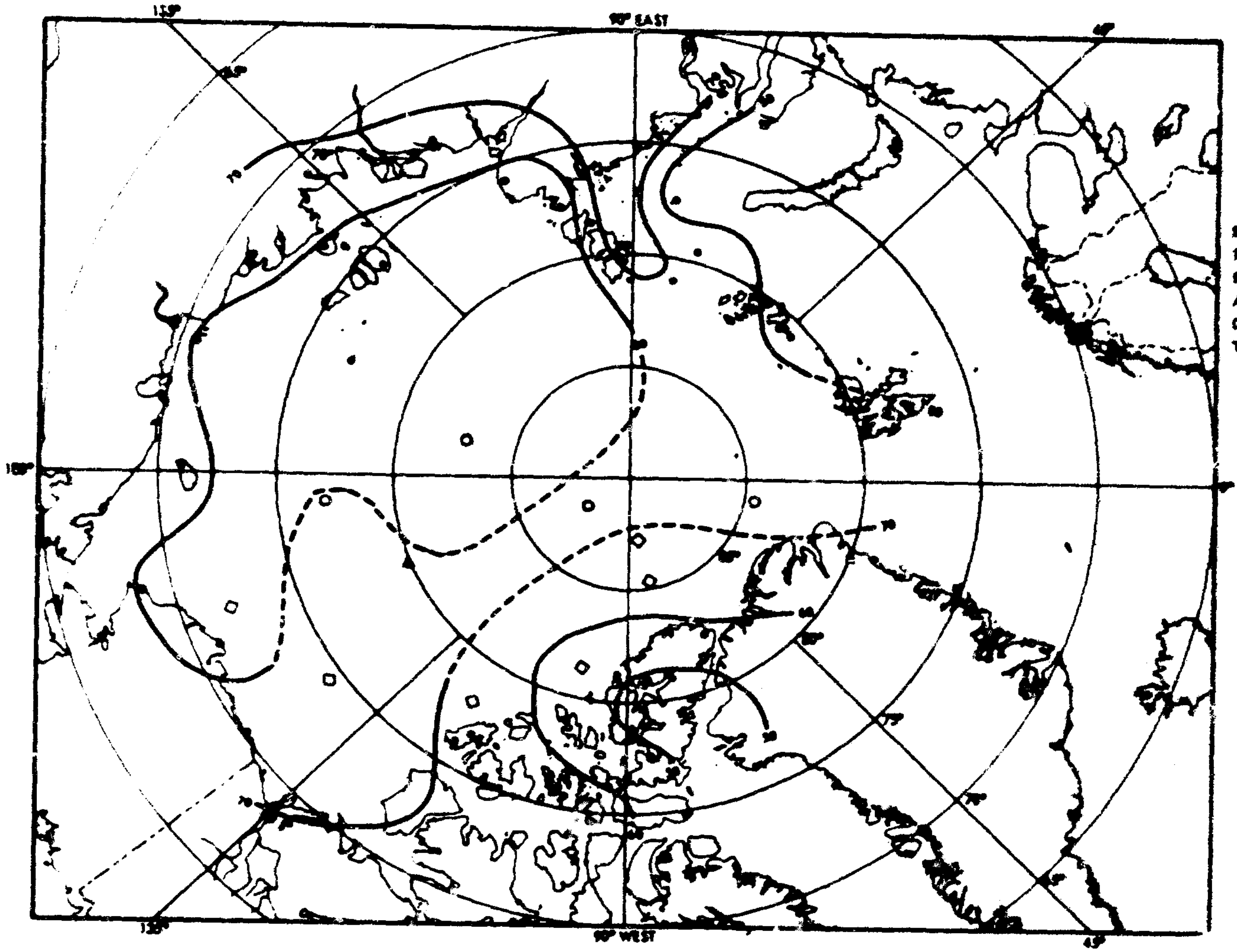
SOLID LINES BASED ON DATA FROM FIXED STATIONS. DASHED LINES BASED ON DRIFTING STATIONS AND AIR RECONNAISANCE FLIGHT DATA, AND IS LESS RELIABLE IN TERMS OF PERIOD OF RECORD.

Figure 7-7: TOTAL CLOUD AMOUNT PERCENTAGE FREQUENCY CLOUDY ($\leq$7/10) APRIL



SOLID LINES BASED ON DATA FROM FIXED STATIONS. DASHED LINES BASED ON DRIFTING STATIONS AND AIR RECONNAISANCE FLIGHT DATA, AND IS LESS RELIABLE IN TERMS OF PERIOD OF RECORD.

Figure 7-8: TOTAL CLOUD AMOUNT PERCENTAGE FREQUENCY CLOUDY ($\leq$7/10) JULY



SOLID LINES BASED ON DATA FROM FIXED STATIONS. DASHED LINES BASED ON DRIFTING STATIONS AND AIR RECONNAISANCE FLIGHT DATA, AND IS LESS RELIABLE IN TERMS OF PERIOD OF RECORD.

Figure 7-9: TOTAL CLOUD AMOUNT PERCENTAGE FREQUENCY CLOUDY ($\leq$7/10) OCTOBER

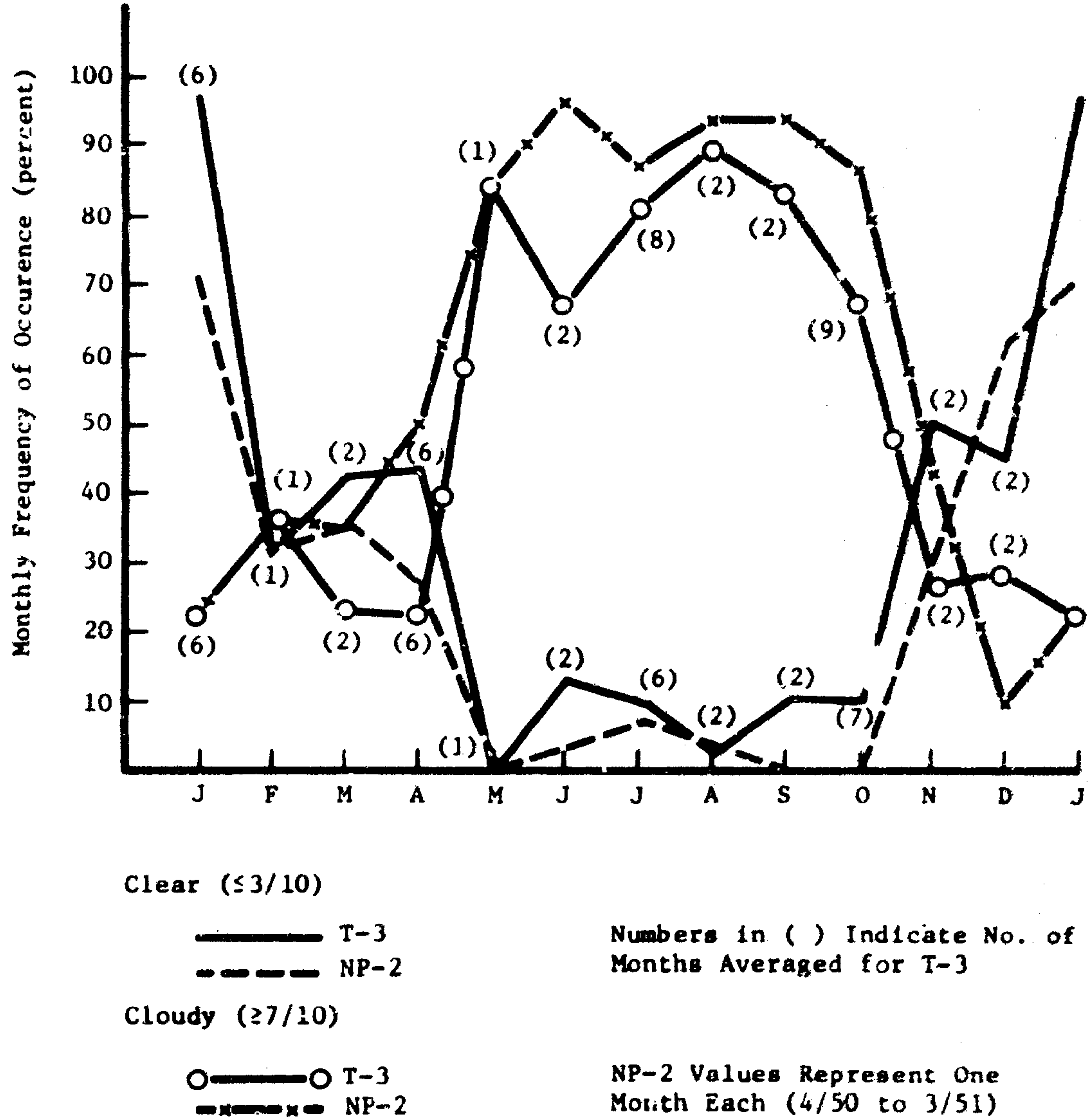


Figure 7-10: ANNUAL CYCLE OF TOTAL CLOUD AMOUNT (ICE ISLAND)

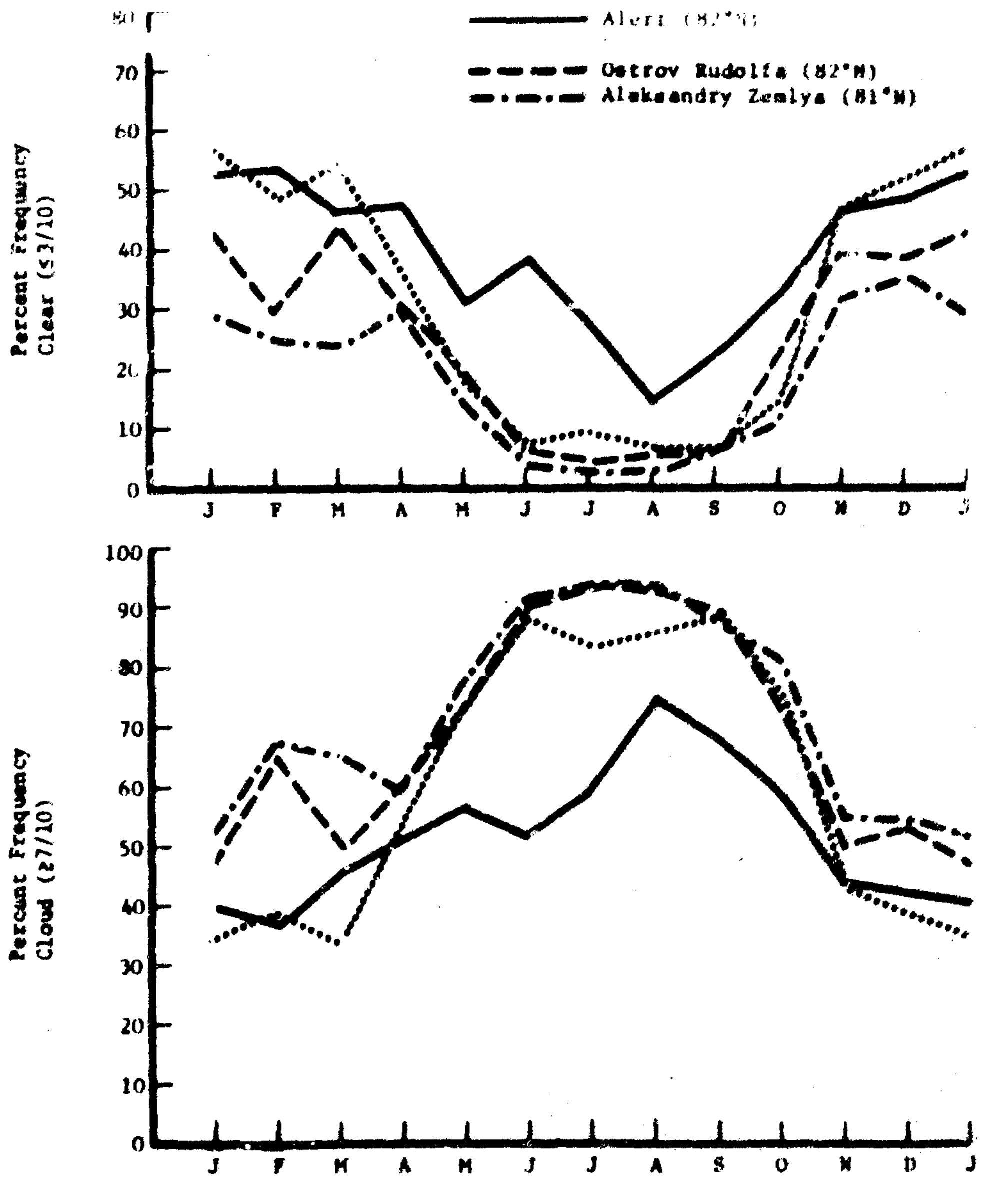


Figure 7-11: ANNUAL CYCLE OF CLOUDINESS AT FIXED-LAND, HIGH-LATITUDE STATIONS

Table 7-3: HEIGHT OF CLOUDS BY TYPE

Cloud Type	Height of Bases, ft (m)			Height of Tops, ft (m)		
	Minimum	Average	Maximum	Minimum	Average	Maximum
Stratus	0 July	800 (250) (116)	4600 (1400) Aug.	500 (150) Sept.	2200 (660) (428)	5900 (1800) Sept.
Stratocumulus	150 (50) July	3000 (900) (200)	8500 (2600) Aug.	1000 (300) Sept.	4300 (1300) (618)	13000 (4000) Oct.
Nimbostratus	150 (50) Aug.	2600 (800) (64)	5900 (1800) Sept.	650 (200) Aug.	4600 (1400) (78)	11500 (3500) Sept.
Altostratus	3300 (1000) Aug. Oct.	8000 (2500) (257)	18000 (5500) April	4600 (1400) Aug.	10500 (3200) (151)	18500 (57 Aug.
Altocumulus	3300 (1000) Oct.	9000 (2700) (274)	18000 (5500) July	4900 (1500) July	10000 (3100) (153)	18000 (5500) April
Cumulus	1300 (400) Sept.	3300 (1000) (14)	4900 (1500) Aug.	2300 (700) July	6600 (2000) (28)	15000 (4500) July
Cumulonimbus	1300 (400) Aug.	3300 (1000) (6)	6600 (1000) Aug.	3300 (1000) Aug.	4300 (1300) (25)	12000 (3700) Sept.
Cirrus	13000 (4000) Aug.	18400 (5600) (46)	21000 (6500) July	---	---- (0)	----
Cirrostratus	13000 (4000) July, Aug.	19000 (5800) (91)	28000 (8500) July	---	---- (0)	----

Reference: Extent of Clouds Over Arctic Seas and Central Arctic USSR, Zavarina, M. V. and M. K. Romasheva, Translation from Russian Problemy Arktiki, No. 2., pp 127-132, Leningrad, 1957, OTS: 60031, 036, JPRS: L-2019-D, 25 Jan. 1960.

Table 7-4: FREQUENCY OF BASES AND TOPS BY CLOUD TYPE AND BY HEIGHT LEVEL (PERCENT)

Layer of Clouds (feet)	Bases								Tops							
	St	Sc	Ns	Cb	Cu	As	Ac	All	St	Sc	Ns	Cb	Cu	As	Ac	All
0 - 650	41	4	11	--	--	---	---	7	3	1	--	--	--	--	--	1
650 - 2000	47	35	34	36	21	---	---	17	42	9	5	--	--	--	--	16
2000 - 3300	8	17	13	28	29	---	---	6	32	23	27	--	21	--	--	21
3300 - 4600	3	17	27	9	29	6	2	9	17	27	24	23	17	--	--	18
4600 - 6000	1	18	11	18	21	16	7	12	5	18	20	27	17	5	1	11
6000 - 7300	--	7	3	9	--	21	16	12	1	11	9	12	12	11	5	10
7300 - 8500	--	2*	1*	--	--	13	18	9	--	11*	15*	38*	33*	13	26	4
8500 - 10000						10	6	4						23	26	5
10000 - 11000						16	27	12						12	17	3
11000 - 12500						9	11	5						9	4	1
12500 - 14000						2	8	3						8	6	11
14000 - 15000						5	2	2						7	4	1
>15000						2	3	1						12	11	2
Number of Cases	116	201	64	11	14	256	257	919	428	617	79	26	24	154	153	1481

*For Heights >7300 feet; not included in cumulative percentages.

Table 7-5: MONTHLY FREQUENCY OF CLOUD BY VERTICAL THICKNESS (PERCENT)

Cloud Thickness (feet)	Months							Number of Cases	Percentage
	April	May	June	July	Aug.	Sept.	Oct.		
300 - 1300	62	86	64	56	37	41	50	105	46
1300 - 2300	14	14	24	38	31	35	38	68	30
2300 - 3300	5	--	8	--	12	16	--	23	10
3300 - 4300	55	--	--	6	10	4	12	15	7
4300 - 5300	14	--	4	--	5	2	--	10	4
5300 - 6300	--	--	--	--	4	--	--	4	2
>6300	--	--	--	--	1	2	--	2	1
Number of Cases	21	7	25	16	99	51	8	227	100

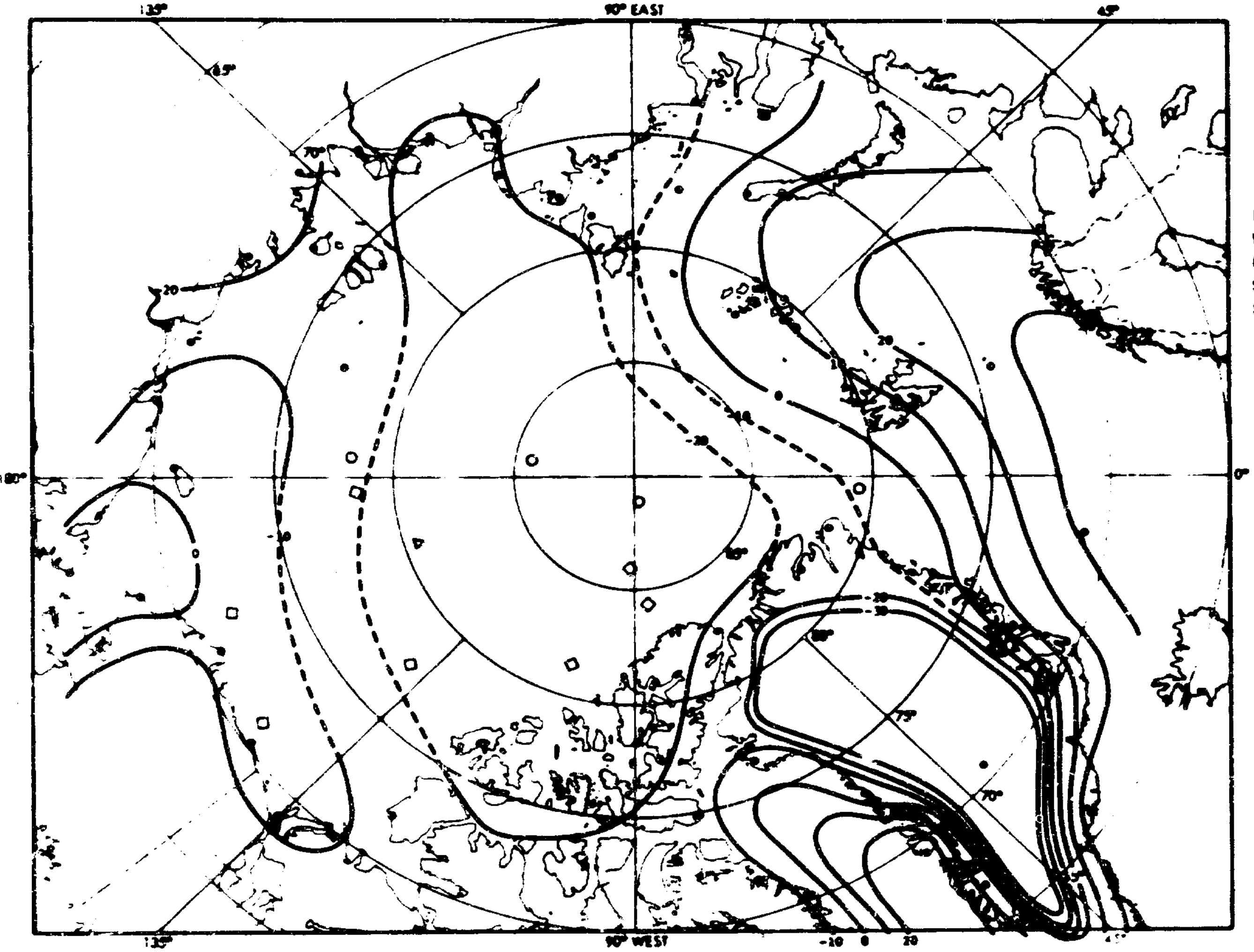
Although the occurrence of clouds is almost constant through the months of June to September, no information is available on cloud types and ceiling heights for winter occurrences. When clouds occur during the dark winter months they are undoubtedly associated with synoptic low-pressure systems that move into arctic latitudes from subpolar regions. Comments on storm movements are contained in Section 7.3.8.

7.3.2 Surface Temperature

Midwinter and midsummer temperature distributions are presented in Figures 7-12 through 7-15. Average daily maximum and minimum values have been obtained for January and July from a somewhat greater number of reporting stations than for cloudiness. The isotherm patterns are based on the perimeter analysis of fixed station data and the drifting ice stations used to complete the analysis across the central arctic regions. In general, the analysis for Greenland is based on coastal station observations and is not representative of the higher interior ice mass (8,000 to 9,000 feet). Therefore, additional isotherms have been drawn consistent with smoothed-height contours to indicate the much cooler temperatures observed over the internal Greenland ice plateau.

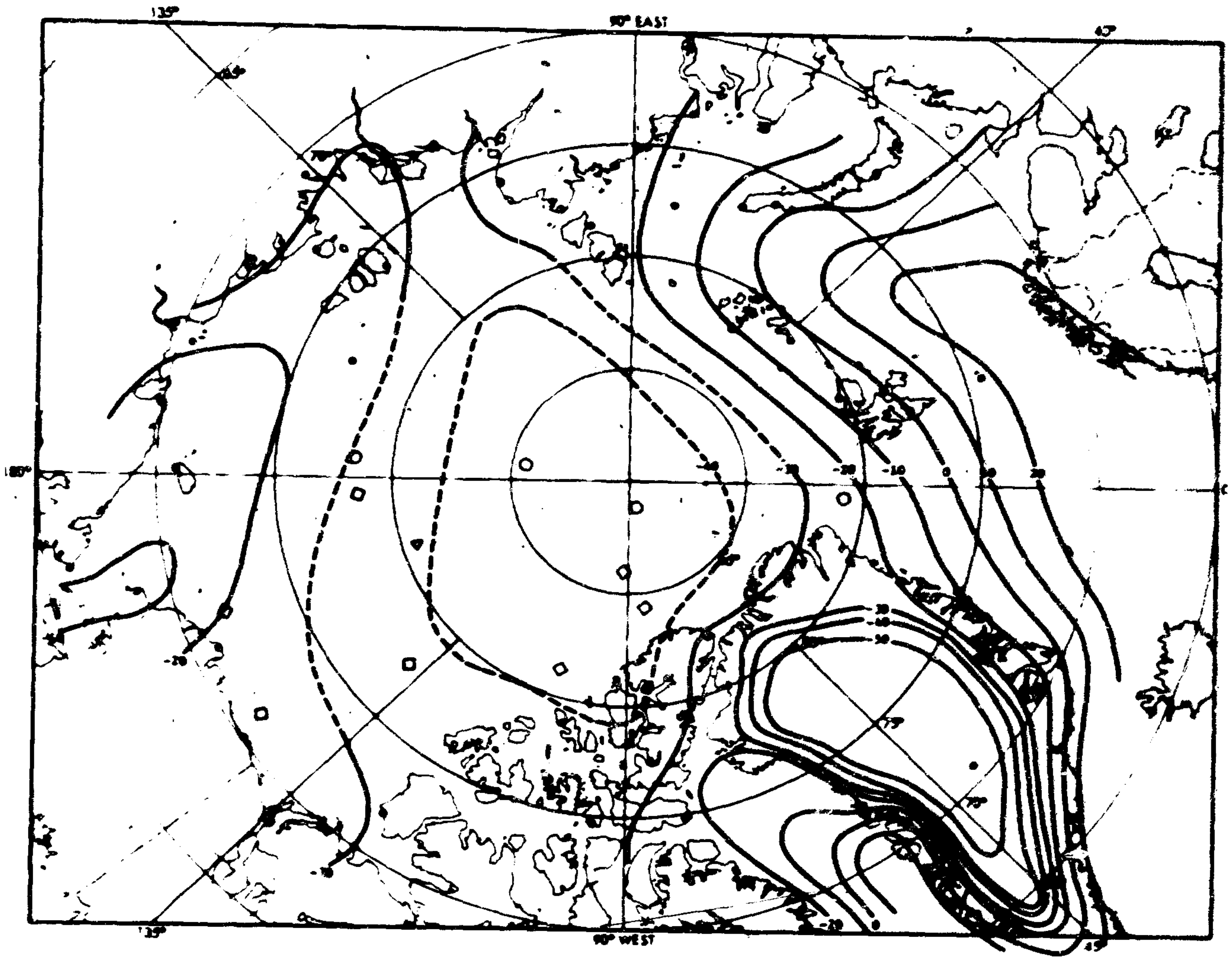
A range exceeding 20°F is noted between the average daily maximum and minimum during January throughout most of the central ice pack region. This is contrasted with the comparable average variation of about 5 degrees indicated in July. The July daily maximum temperature only slightly above freezing shows the great influence that results from open-water and melt-water areas within the ice pack. It can also be stated that the temperature distribution is considerably more uniform over the ice pack in July than during January.

The annual temperature cycle derived from drifting ice stations (T-3 and NP-2) is shown in Figure 7-16. The mean monthly temperatures are depicted by the solid line for T-3 based on about 5 years' data, and by the dashed line for NP-2 based on a single year's data. The agreement between these two sets of data is satisfactory, and is considered as representing the mean temperature cycle of the central Arctic Basin. Also shown in Figure 7-16 are bars illustrating the total range of temperatures observed at these stations. These values represent the extremes reported during the years of record. Of interest is the contrast in range noted between the months of September to April and the months of May to August. The small variation observed in the summer season is undoubtedly the result of the extensive cloud cover during this period. The large variations observed during the other months are also a function of sky cover. When clouds prevail, temperatures may be 10 to 20 degrees higher than during comparable clear periods. Since cloudiness in the winter period is brought about by storm movement, some of the observed temperature increase is the result of temperature advection as well. Because of this feature, day-to-day



ISOTHERMS ARE SOLID LINES WHERE DATA ARE BASED ON PERIOD OF RECORD FROM FIXED STATIONS. DASHED LINES ARE SUGGESTED BY DATA EXTRACTED FROM DRIFTING STATIONS.

Figure 7-12: SURFACE TEMPERATURE AVERAGE DAILY MAXIMUM (^{o}F) JANUARY



ISOTHERMS ARE SOLID LINES WHERE DATA ARE BASED ON PERIOD OF RECORD FROM FIXED STATIONS. DASHED LINES ARE SUGGESTED BY DATA EXTRACTED FROM DRIFTING STATIONS.

Figure 7-13: TEMPERATURE AVERAGE DAILY MINIMUM (^{o}F) JANUARY

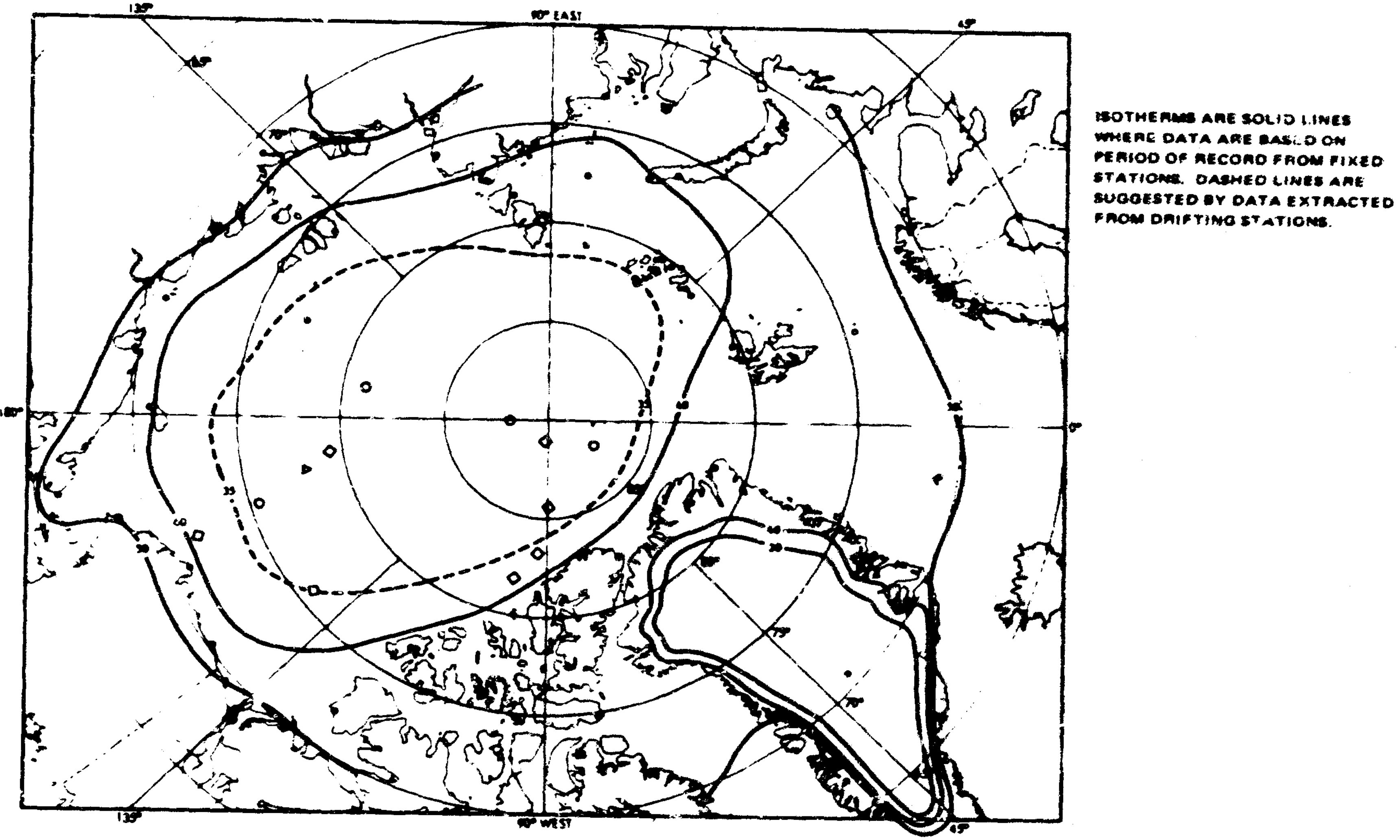
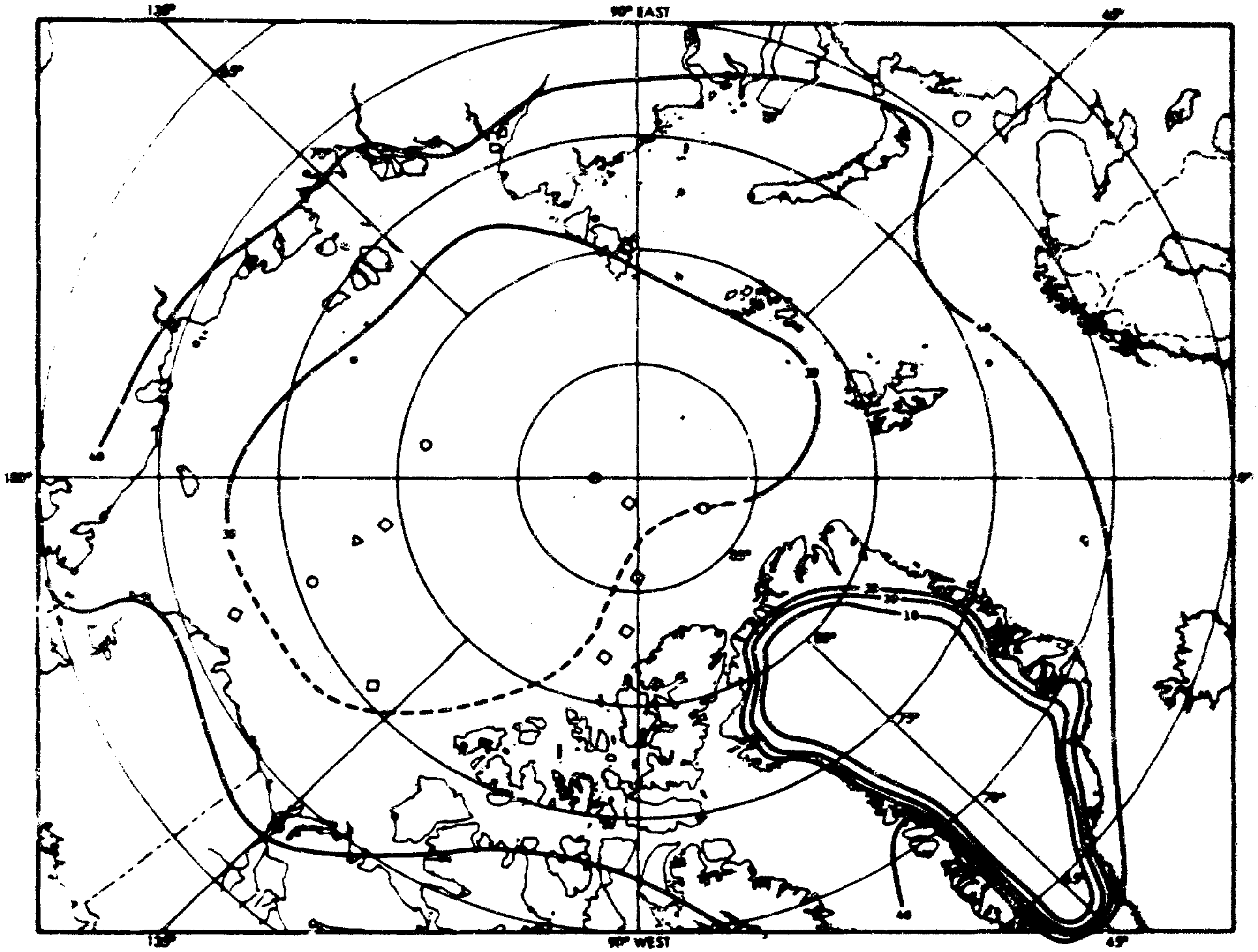


Figure 7-14: TEMPERATURE AVERAGE DAILY MAXIMUM (^{o}F) JULY



ISOTHERMS ARE SOLID LINES WHERE DATA ARE BASED ON PERIOD OF RECORD FROM FIXED STATIONS. DASHED LINES ARE SUGGESTED BY DATA EXTRACTED FROM DRIFTING STATIONS.

Figure 7-15: TEMPERATURE AVERAGE DAILY MINIMUM ($^{\circ}F$) JULY

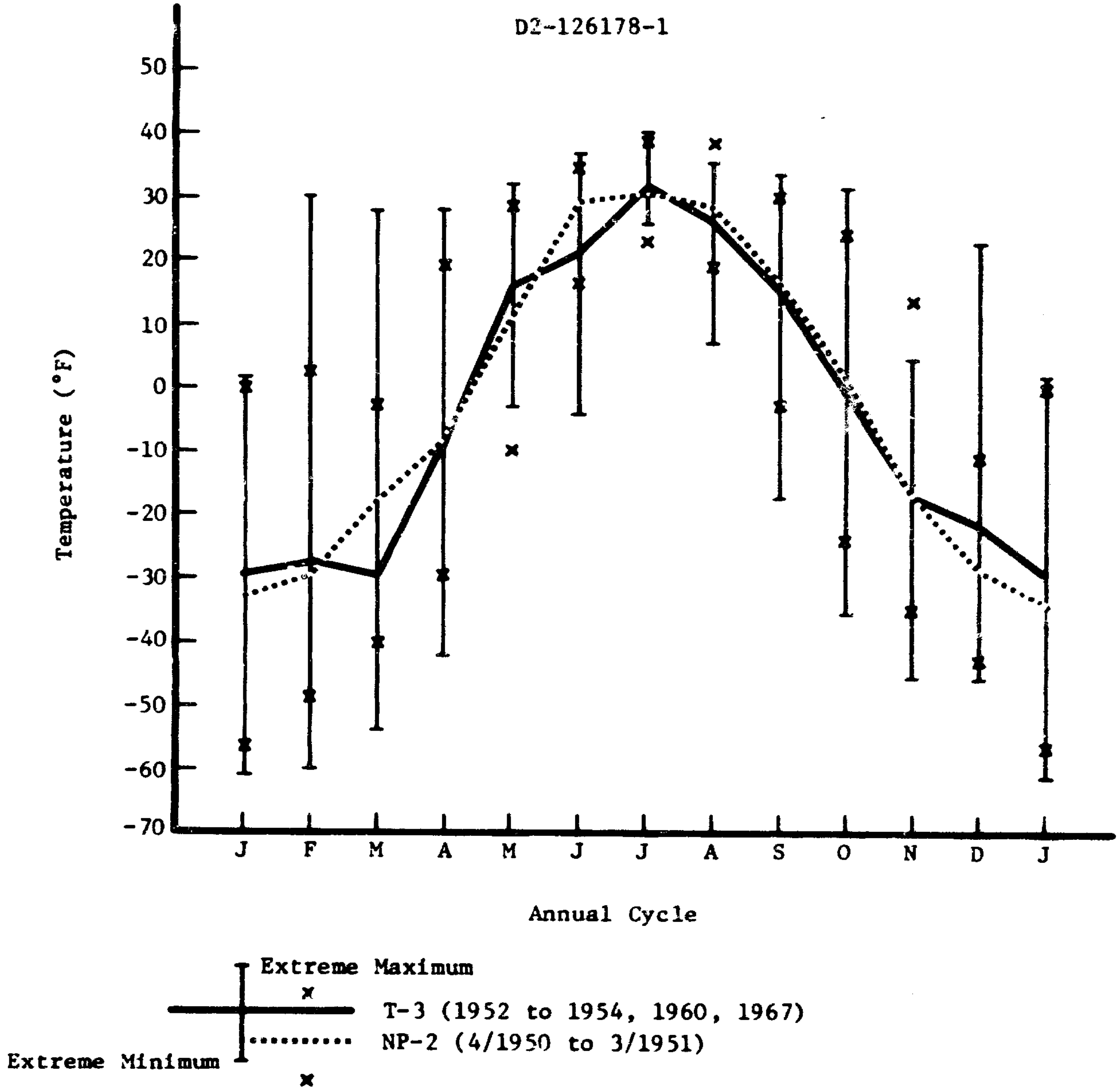


Figure 7-16: ANNUAL TEMPERATURE DISTRIBUTION (ICE ISLAND)

changes in maximum or minimum temperatures can be quite large during winter months (as much as 30°F), whereas during summer months very little variation occurs (<5°F).

A remarkable example of the change in temperature associated by passage of a storm system occurred at T-3, January 11 to 13, 1958. On the 10th conditions were: the maximum and minimum temperatures, -20 and -50°F; scattered altocumulus clouds; and winds northwest at 9 knots. During the 11th the storm advanced rapidly: the minimum temperature observed was still -52°F, but the maximum had warmed to +2°F; the sky cover had become overcast, stratiform. The winds switched from northwest to north at 15 knots. By the 12th the full effect of the storm had brought the maximum temperature to +5°F and the minimum to -24°F, with overcast skies and north winds at 15 knots. On the 13th the skies cleared and the wind increased to 26 knots. It was not until some 15 days later that the effects of this storm system and associated air mass characteristics passed allowing minimum temperatures again to drop below -40°F. This storm sequence is evident also in the records of Isachsen, Northwest Territories (located some 150 nautical miles south of T-3 at this time). Related data for the period of January 12 to 13 are given in Table 7-6.

Table 7-6: STORM SEQUENCE AT ISACHSEN, NWT

Date	Time (MST)	Temp. (°F)	Pressure (mb)	Sky Cover (tenths)	Wind Direction	Wind Speed (mph)
Jan. 12	02	-41	1019.1	0	Calm	
	05	-37	1018.4	0	Calm	
	08	-33	1014.6	10	N	20
	11	-08	1010.5	10	N	32
	14	-14	1008.3	10	N	45
	17	-20	1006.7	10	N	48
	20	-19	1005.1	10	N	40
	23	-18	1001.4	10	N	54
Jan. 13	02	-15	999.6	10	N	50
	05	-13	1000.2	10	N	70
	08	-12	1003.2	10	N	20
	11	-15	1006.1	10	N	50
	14	-16	1010.9	0	N	16

This example may be considered as a rare event for the central arctic, but is indicative of the rapidity with which changes can occur during the arctic winter. As discussed in Section 7.3.8, the likelihood of such strong storm situations is reduced as one proceeds toward the central ice pack.

Figures 7-17 and 7-18 describe the annual temperature cycle for stations in the Canadian Archipelago and north coastal Greenland. The ice island mean of Figure 7-16 is 5 to 10 degrees colder than a mean based on Figures 7-17 and 7-18. The extremes noted on the ice island are many degrees less than those shown for the land stations.

7.3.3 Vertical Temperature Profile

In the example described above, the sharp increase in temperature was judged to have resulted from the effects of the increased cloud cover and advective processes. It is also possible that as a result of the strong increase in winds, turbulent mixing brought warmer air toward the surface from aloft. Belmont summarized the first year's upper air data from T-3 to show the characteristic inversion in temperature profile that occurs during the winter months. The January and July monthly mean profiles at T-3 are presented in Figure 7-19. Mixing of air in the lowest 1,000 feet could raise the surface temperature by about 15°F (Reference 5).

As a result of the continued observations from ice islands, and in particular data from the Russian NP-4, 6, and 7 stations, Vowinckel and Orvig have composed a climatology of polar inversions. Selected information from this report has been extracted and is presented in Table 7-7. The data are presented for midseasonal months, cases of no inversion, surface inversions, and upper inversions, and by conditions of clear skies or low-cloud coverage. A surface inversion is designated when the temperature increases with altitude directly above the surface, whereas the upper inversion occurs at some higher level. As indicated in Table 7-6 the maximum temperature in upper inversions often exceeds the suface temperature (Reference 6).

Vowinckel and Orvig state that inversions may be caused by radiative cooling during clear skies, subsidence of air during stable conditions, and advection of warm air at any height. The interaction of all these factors makes analysis of a particular inversion complicated. Vowinckel and Orvig claim the polar inversion reaches to 2,000 meters during its maximum in the winter months. Upper inversions are most frequent from May to September. The upper inversion during summer is undoubtedly associated with the occurrence of the observed stratiform cloud cover.

The data presented in Table 7-7 shows inversions to be less intense during cloudy conditions, and occur at higher altitudes under clear sky conditions. If the clouds break up or become

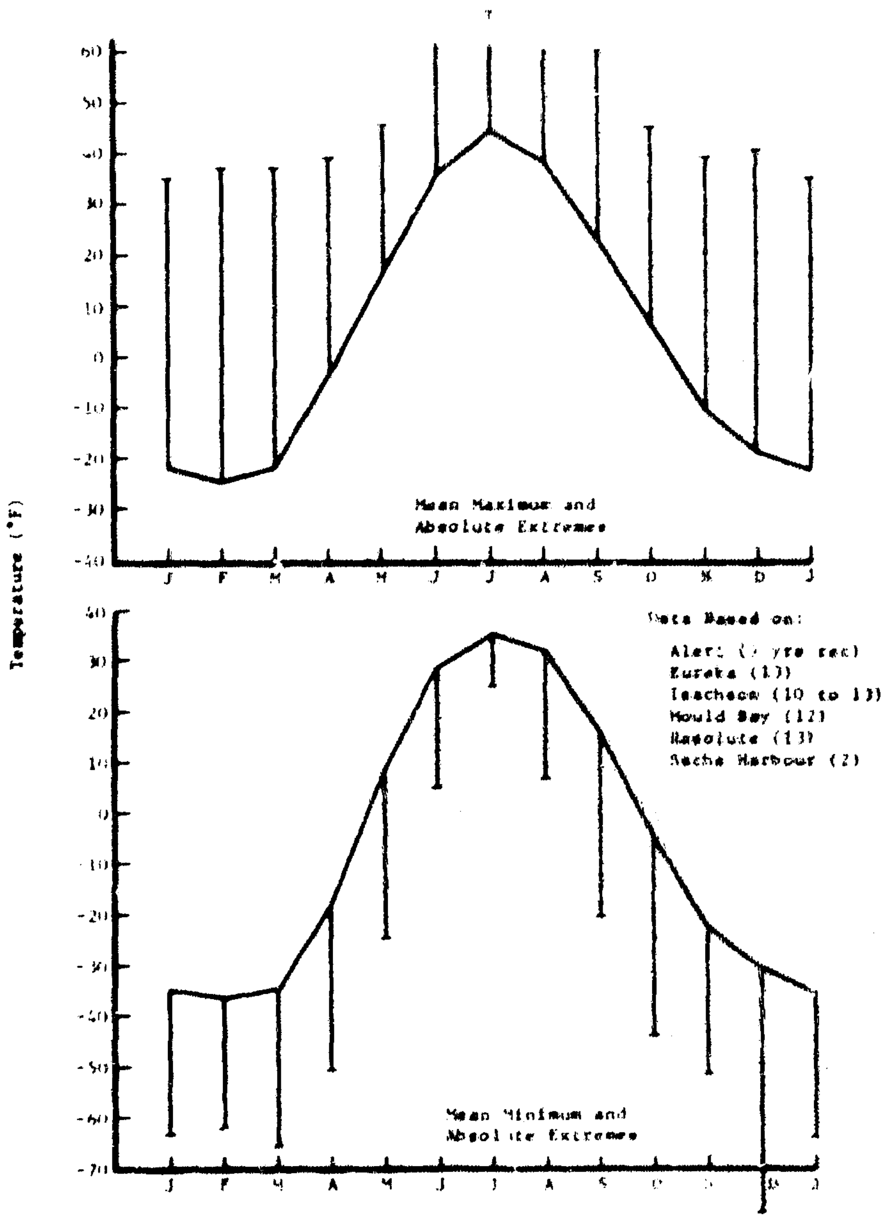


Figure 7-17: ANNUAL TEMPERATURE CYCLE---CANADIAN ARCHIPELAGO

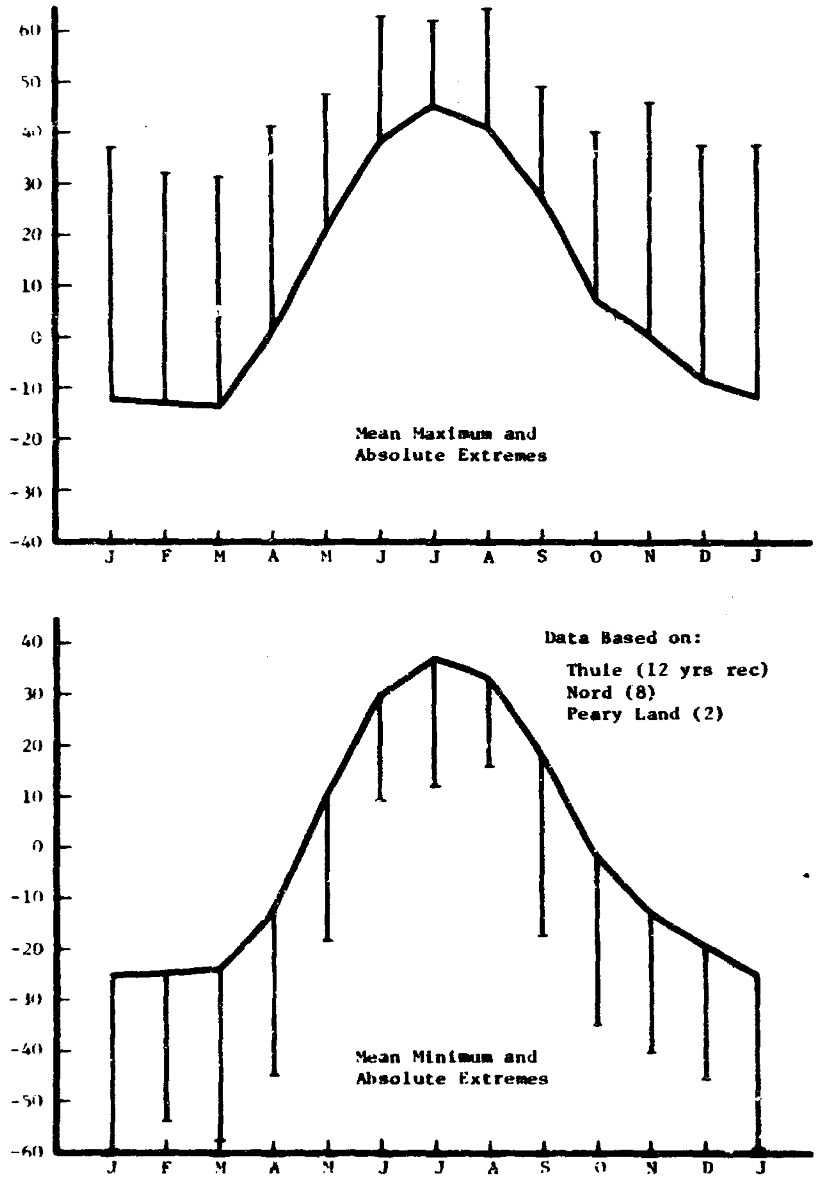


Figure 7-18: ANNUAL TEMPERATURE CYCLE---NORTH GREENLAND COASTAL STATIONS

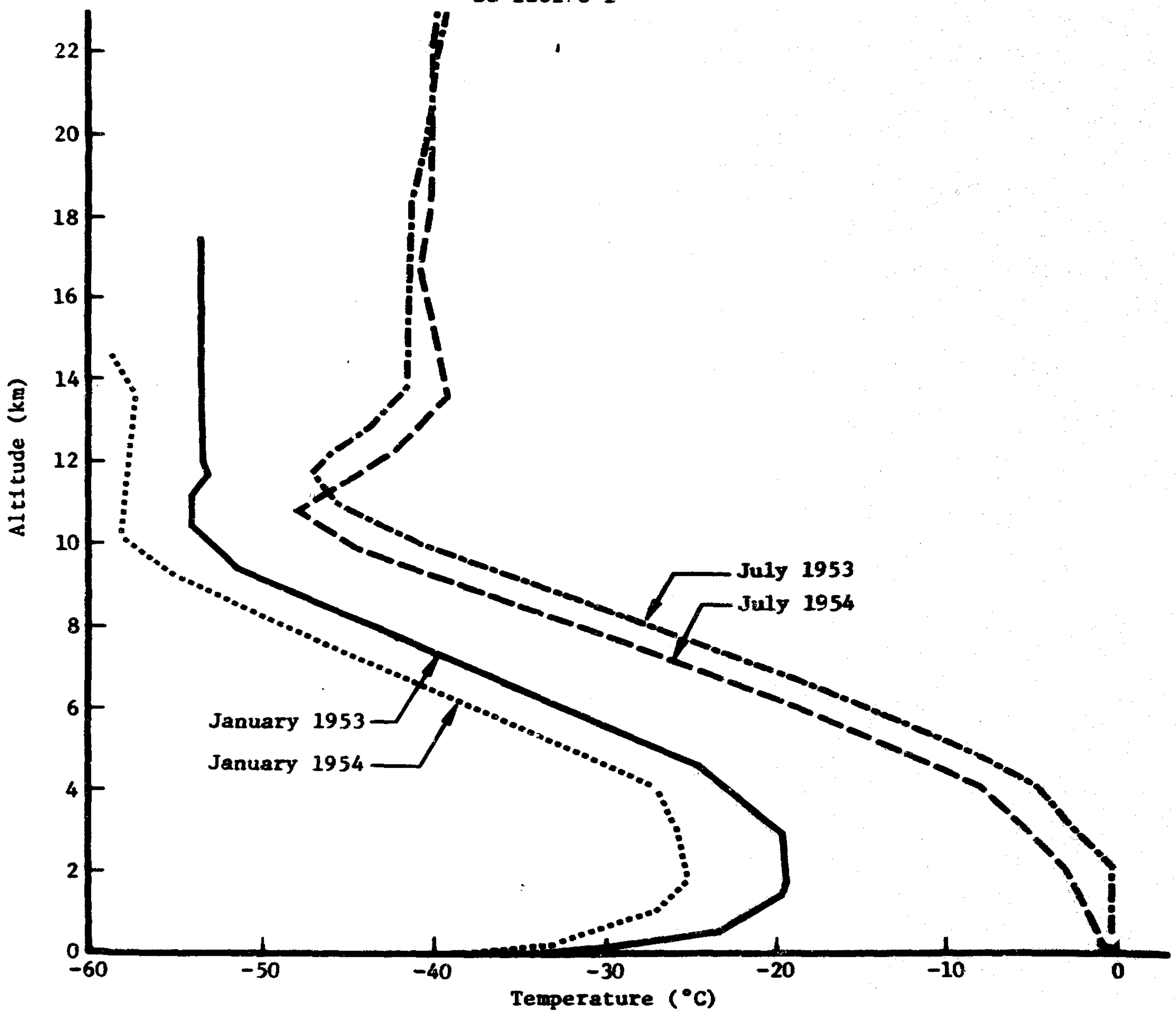


Figure 7-19: VERTICAL TEMPERATURE PROFILES, T-3 (Ref Belmont, 1959)

Table 7-7: POLAR INVERSIONS

	Winter	Spring	Summer	Fall
Freq. Dist. By Type				
No Inversion	2	7	28	10
Surface	82	65	29	57
Upper	16	28	43	33
Mean Wind Speed (m/sec)				
No Inversion	7.7	3.7	6.0	4.9
Surface	4.3	4.2	5.2	5.0
Upper	7.4	5.8	5.8	4.9
Mean Duration (hours)				
No Inversion	20.5	21.5	32.5	15.5
Surface	97.5	100.0	24.0	54.0
Upper	18.0	27.5	32.5	26.5
Mean Cloud Amt (%)				
Surface	53	50	79	43
Upper	94	93	99	97
Surface Temp. (°C)				
Clear	-36.6	-28.6	-2.6	-27.4
10/10 Low Cloud	-24.3	-21.8	-0.6	-18.6
Max. Temp. in Inversion (°C)				
Clear	-26.4	-18.5	+2.1	-19.5
10/10 Low Cloud	-17.0	-15.0	+3.3	-13.6
Ht. of Max. Temp. (meters)				
Clear	165	145	98	148
10/10 Low Cloud	138	139	102	107
Freq. that Max. Temp. In Upper Inversion Exceeds Surface Temp. (%)	92	67	41	49
UPPER INVERSION				
Surface Temp. (°C)				
Clear	-21.8	-23.3	-0.5	-27.6
10/10 Low Cloud	-26.8	-14.9	0.0	-13.9
Average	-24.8	-15.5	0.8	-13.6

Table 7-7: POLAR INVERSIONS (continued)

	Winter	Spring	Summer	Fall
Base Height (m)				
Clear	25	22	63	13
10/10 Low Cloud	57	49	77	68
Average	60	40	42	66
Top Height (m)				
Clear	104	168	122	133
10/10 Low Cloud	176	121	146	142
Average	171	148	76	142
Vert. Temp. Change (°C)				
Clear	6.4	6.2	0.8	1.4
10/10 Low Cloud	6.7	5.7	1.6	3.3
Average Temp. In				
Upper Inversion (°C)	-8.7	-6.1	+2.2	-3.4

Reference: Vowinckel and Orvig, 1967.

comparatively thinner, the upper inversion should revert to a surface-type inversion under conditions of radiative development. During the summer months, the upper inversion will break down only if the surface temperature exceeds the maximum temperature of the inversion.

A distribution of winter surface inversion frequency, intensity, and height is presented in Figures 7-20 through 7-22, taken from Vowinckel and Orvig's paper.

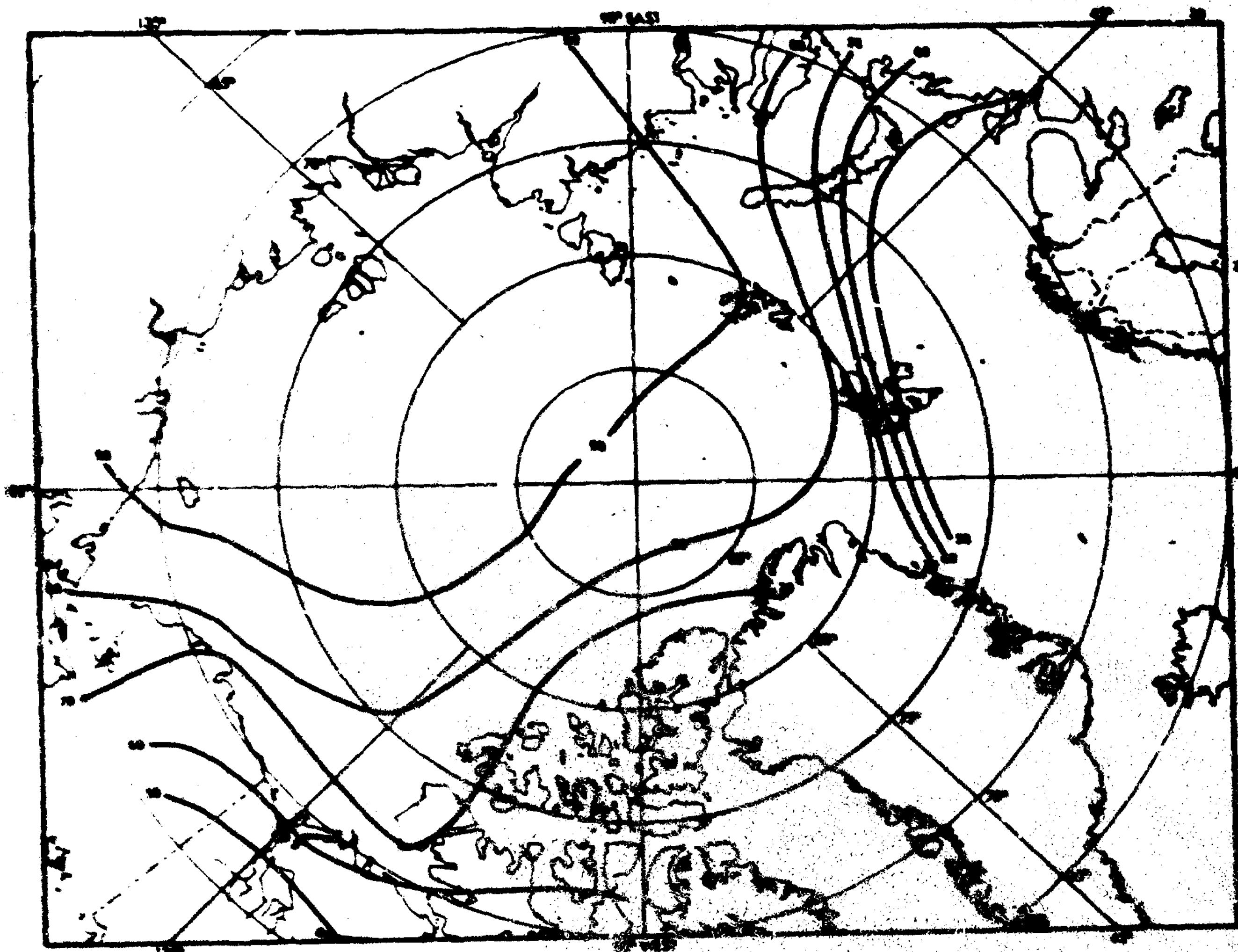
7.3.4 Surface Visibility

A number of phenomena are peculiar to the arctic which effect the visibility observed. One is the frequency of blowing snow and others are ice fogs and "white-outs." The quantity of snow that falls is not large and is discussed in a later section, but the extreme cold combines with high winds to create frequent blowing snow. From a cursory examination of records from the ice island stations, blowing snow is reported whenever winds exceed 15 mph although on some occasions winds were as low as 10 mph. The effect on reducing overall visibility is greater as the wind speed increases and/or the duration of high winds increases. Blowing snow has been reported over periods as long as 4 days.

Ice fogs are described as fogs composed of suspended ice crystals and ice droxtals (particles formed by direct freezing of supercooled water droplets at temperatures below -30°C). Ice fogs increase in frequency as the temperature decreases, and are almost always present when temperatures of -45°C occur near a water vapor source. Sources of water vapor are often consistent with human or animal habitation, and therefore ice fogs are generally of somewhat localized extent. They are rarely observed at temperatures above -30°C. The more conventional advective and radiative type fogs are most frequent during summer, primarily in the vicinity of the open water regions surrounding the central ice pack. These fogs are not often so dense as to give the lowest visibilities. The persistence of fog conditions in the arctic can be longer than 4 or 5 days on occasion, but commonly are less than 24 hours.

The white-out phenomenon is an optical condition caused by the lack of contrast between the and the snow cover, and while visibility may or may not be reduced, disorientation often occurs. The frequency of occurrence of white-out conditions is not well documented and may present considerable difficulty during the polar summer.

Visibility information for the arctic is not particularly reliable as the degree of subjectivity in its observation is high. There is usually a lack of natural targets to reliably determine distances. Within the ice island observations noticeable differences appear in the systems being used and in the consistency and reliability of the observers. Nevertheless, visibility records



REF: VOWINCKEL & ORVIG, 1967

Figure 7-20: PERCENTAGE FREQUENCY OF SURFACE INVERSIONS WINTER

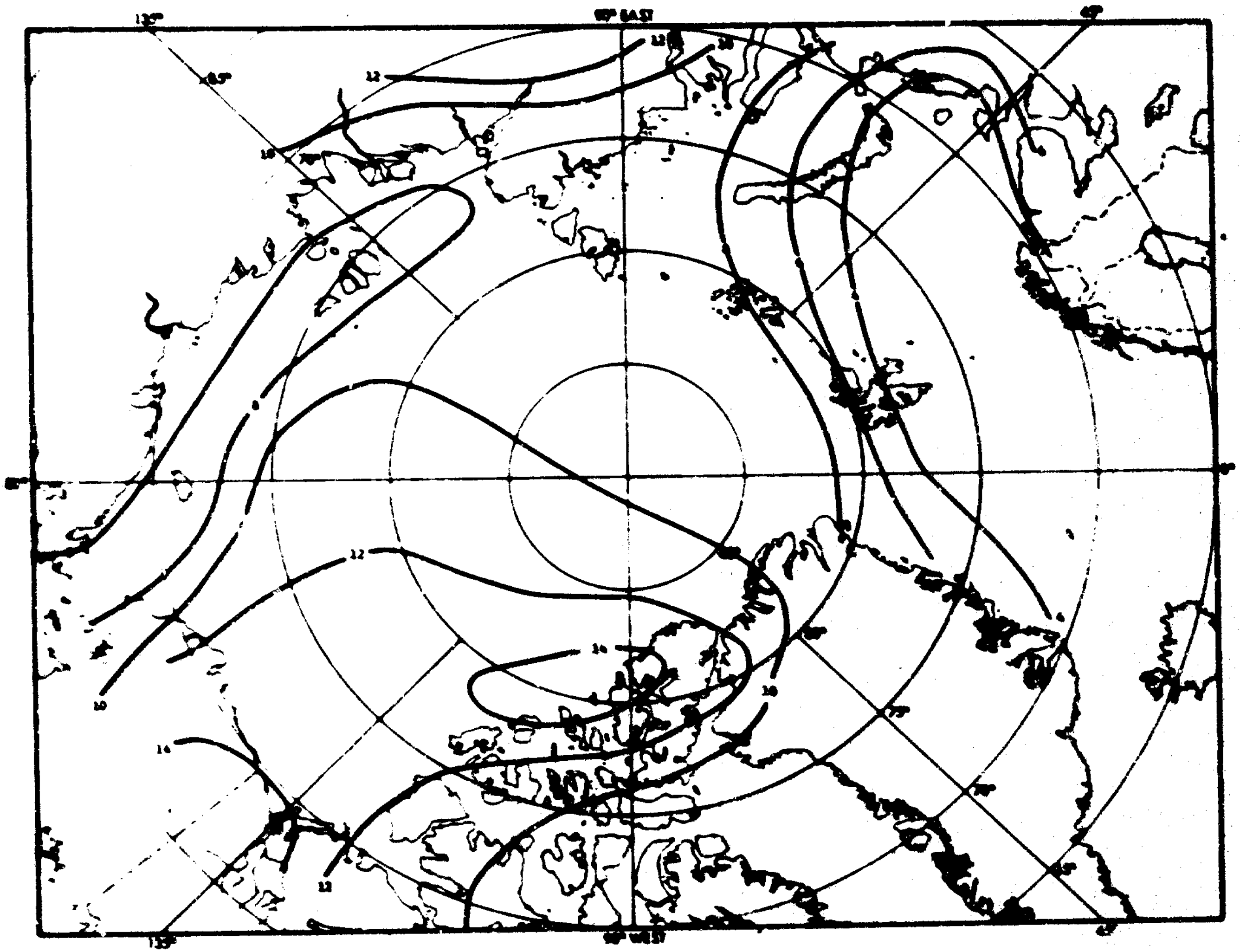
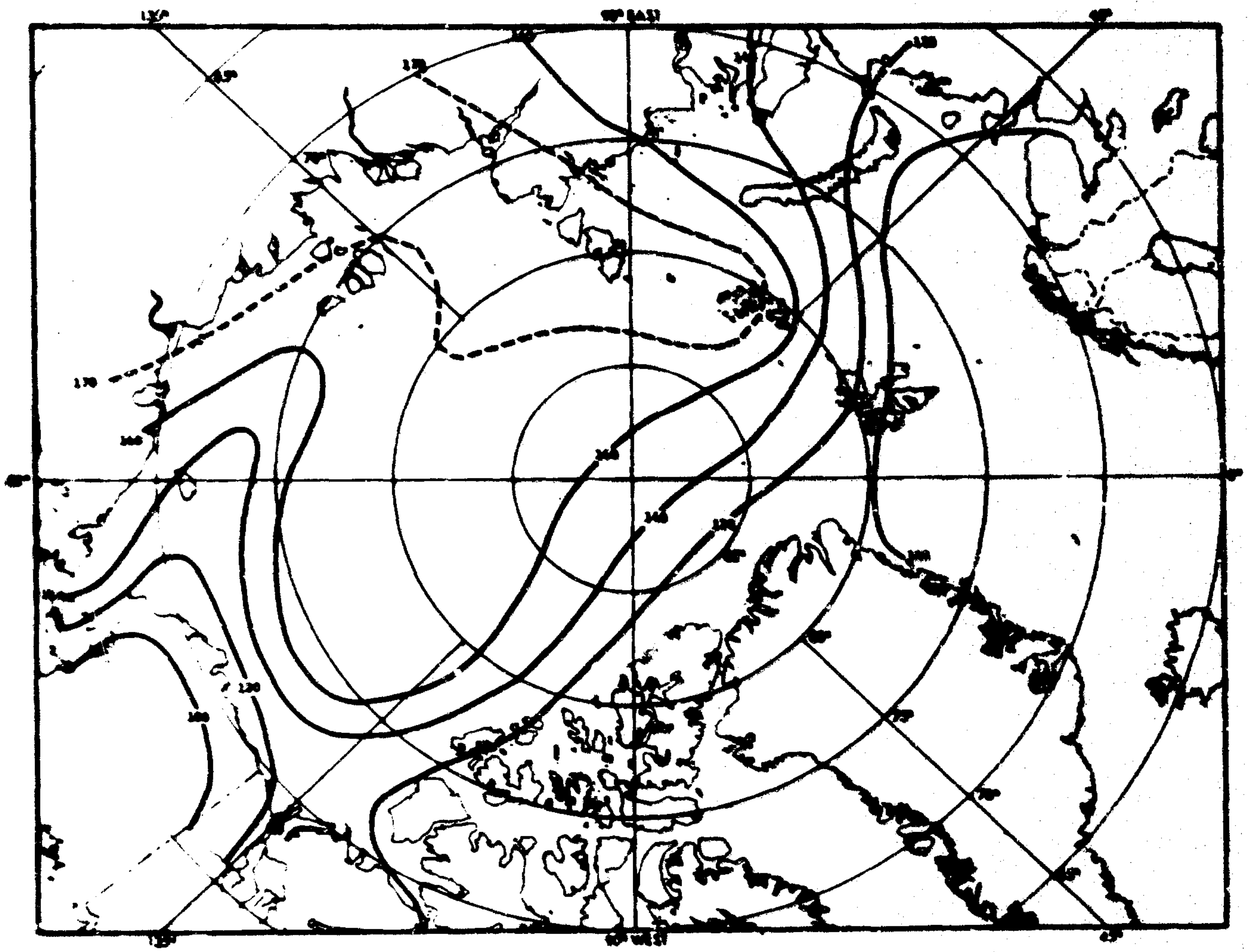


Figure 7-21: INTENSITY OF SURFACE INVERSIONS (°C) WINTER



REF: VOWINCKEL & ORVIG, 1967

Figure 7-22: HEIGHT OF MAXIMUM TEMPERATURE IN SURFACE INVERSIONS (METERS) WINTER

are summarized in the U. S. Navy Marine Climatic Atlas which gives an indication of conditions in the central arctic. Seasonal data has been extracted from this source and is presented in Figures 7-23 to 7-26 (Reference 7).

7.3.5 Surface Winds

The example of rapid temperature change referred to in Section 7.3.2 also showed a marked changeability in surface winds. The greatest wind speeds are associated with intruding storm systems, as was the case in the example. Wind speeds have been evaluated for the three ice islands considered in this study (T-3, Arlis II, and NP-2), and a bar diagram of wind speed frequency is shown in Figure 7-27 based on the total sample from these stations. Little annual variation is noted between the respective frequencies through the midseasonal months. Very few high winds (>27 knots) are observed.

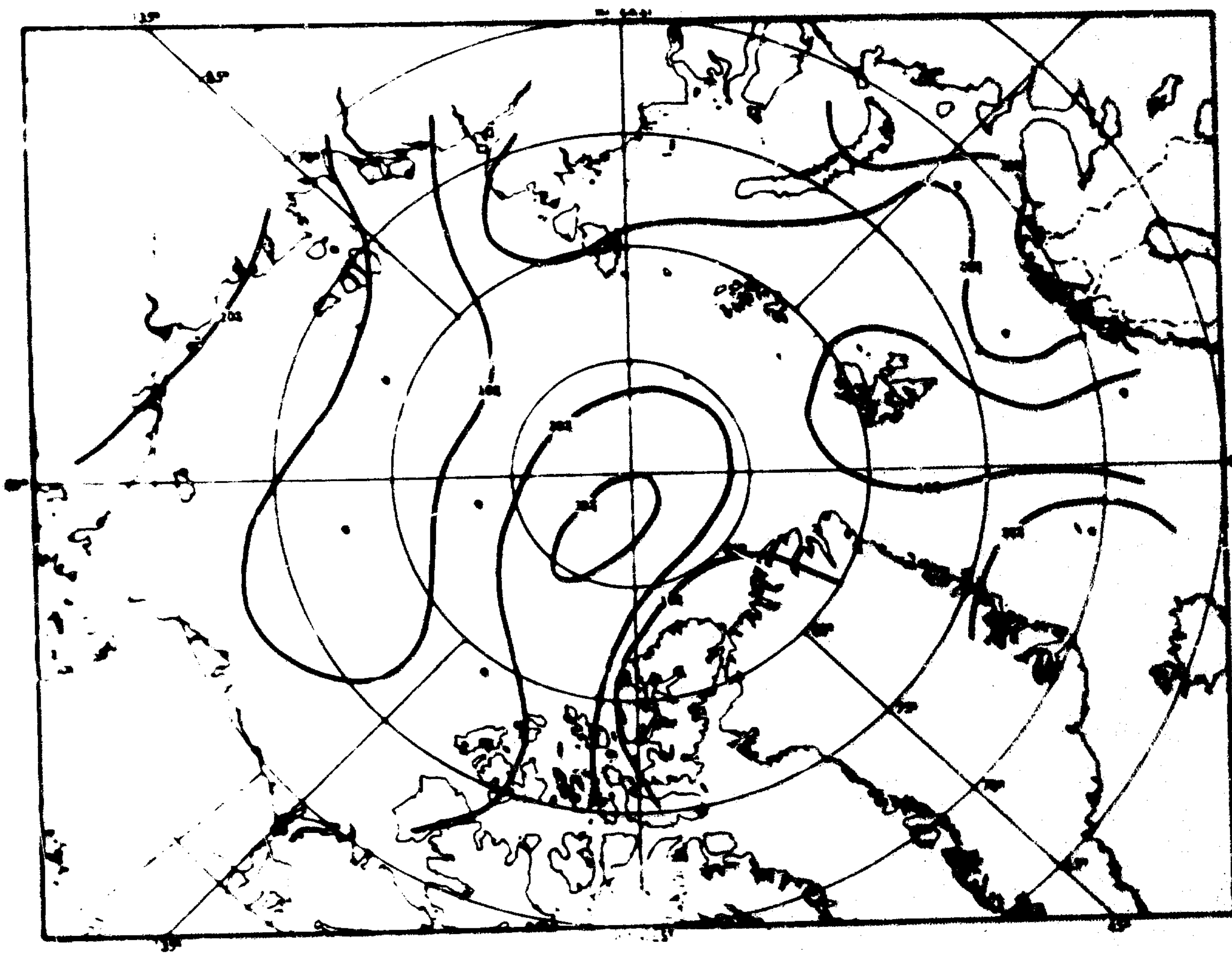
From an examination of ice island records (T-3, Arlis II, and NP-2) the fastest mile wind speeds observed do not exceed a value of 60 mph. October 1960 reported a fastest mile of 52 mph and many winter months show values in the forties. Periods of high wind speed (exceeding 10 mph), in excess of 4 days, are found in these records. Often such occurrences are accomplished by blowing snow and reduced visibility.

The wind-chill index describes the cooling effect or heat loss caused by combinations of strong winds and cold temperatures. The index is expressed in kilogram-calories per square meter per hour of exposure of bare skin based on an average body size. A chart presenting the mean wind-chill index for the coldest month has been extracted from the U. S. Navy Marine Climatic Atlas and is shown in Figure 7-28. Frequency distributions of nonexceedance values are presented by month. In general, the body feels cold for indices above 800, and flesh freezes when the index exceeds 1400 (Reference 7).

Wind directions have been ignored in this summary since as one approaches the pole a difficulty arises in establishing meaningful directions. It is also noted that little, if any, predominant directions are reported from ice island observations. There can be no terrain influence over the ice pack and wind directions are primarily the result of synoptic storm influences.

7.3.6 Precipitation

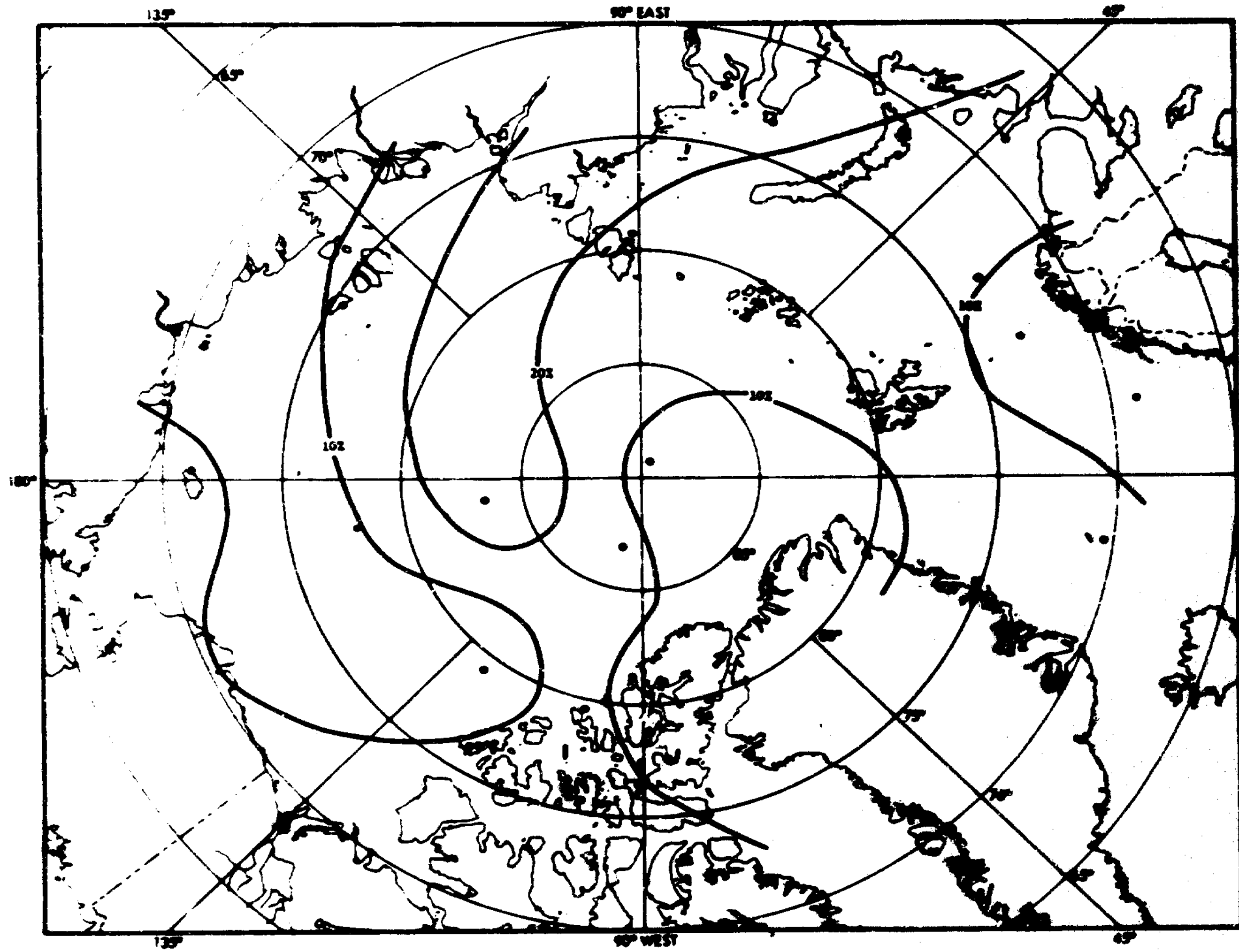
Precipitation, either in liquid or frozen form, occurs throughout the year in the central arctic. The seasonal distribution of both forms presented in Figures 7-29 through 7-32 are taken from the U. S. Navy Marine Climatic Atlas. For some of the arctic region, it precipitates roughly



% OF ALL OBSERVATIONS REPORTING VISIBILITY LESS THAN 2 NM AT GROUND LEVEL DUE TO ALL CAUSES.

REF: U.S. NAVY MARINE CLIMATIC ATLAS OF THE WORLD VOL VI ARCTIC OCEAN NAVWEPS 50-1C-533, 1963

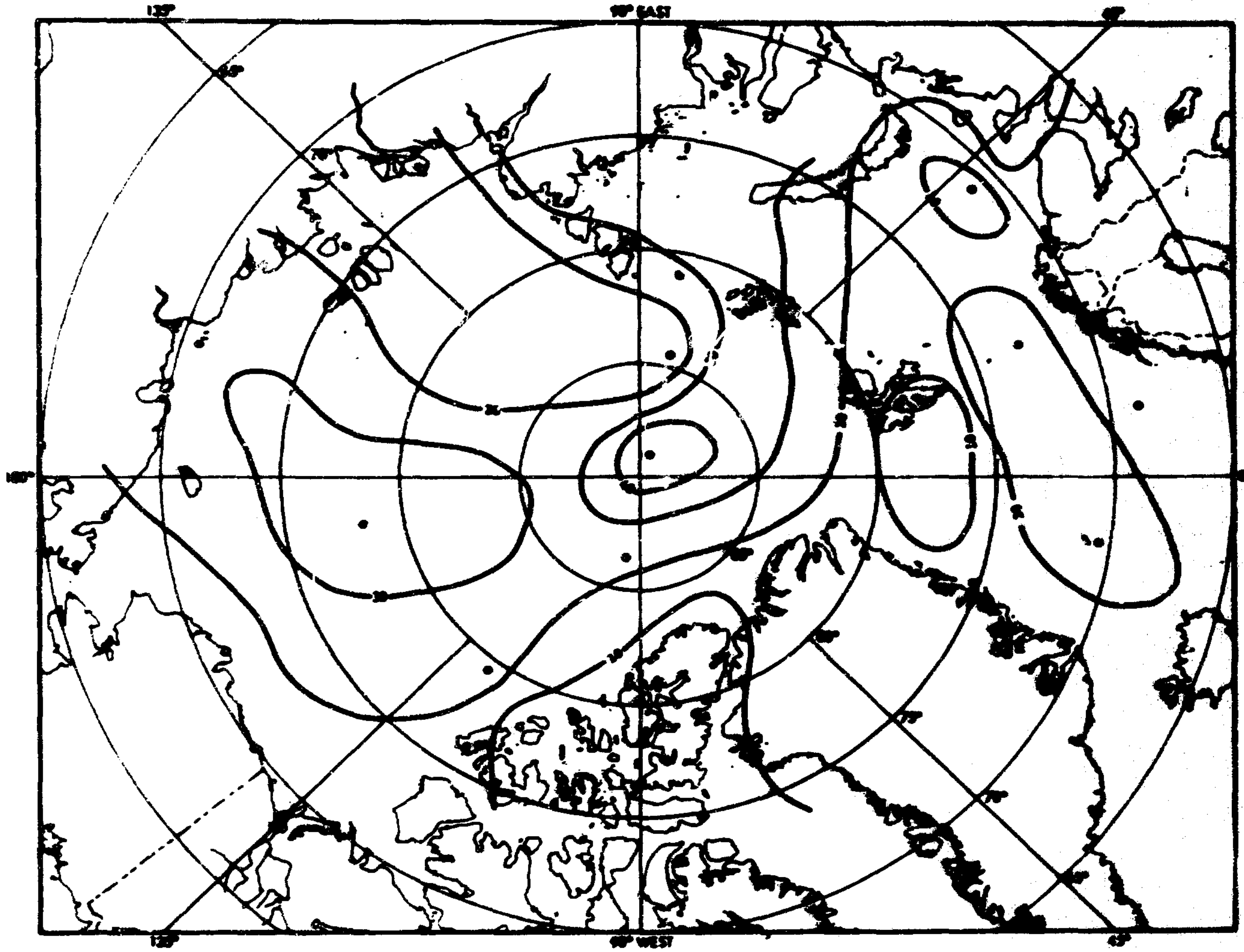
Figure 7-23: LOW VISIBILITY JANUARY



% OF ALL OBSERVATIONS REPORTING VISIBILITY LESS THAN 2 NM AT GROUND LEVEL DUE TO ALL CAUSES.

REF: U.S. NAVY MARINE CLIMATIC ATLAS OF THE WORLD
VOL VI ARCTIC OCEAN NAVWEPS 50-1C-532, 1963

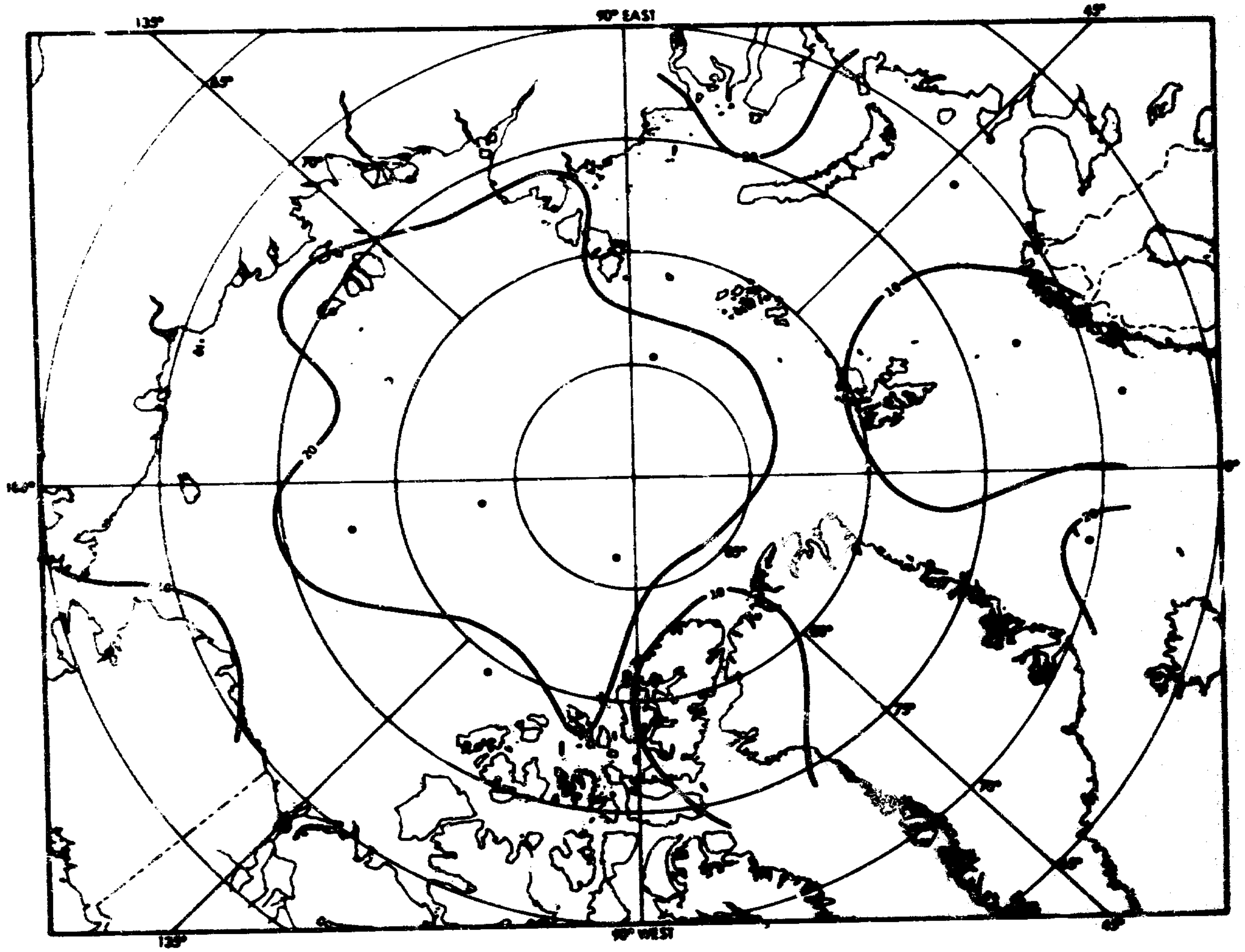
Figure 7-24: LOW VISIBILITY APRIL



% OF ALL OBSERVATIONS REPORTING VISIBILITY LESS THAN 2 NM AT GROUND LEVEL DUE TO ALL CAUSES.

REF: U.S. NAVY MARINE CLIMATIC ATLAS OF THE WORLD
VOL VI ARCTIC OCEAN NAVWEPS 50-1C-532, 1963

Figure 7-25: LOW VISIBILITY JULY



% OF ALL OBSERVATIONS REPORTING VISIBILITY LESS THAN 2 NM AT GROUND LEVEL DUE TO ALL CAUSES.

REF: U.S. NAVY MARINE CLIMATIC ATLAS OF THE WORLD VOL VI ARCTIC OCEAN NAVWEPS 50-1C-532, 1963

Figure 7-26: LOW VISIBILITY OCTOBER

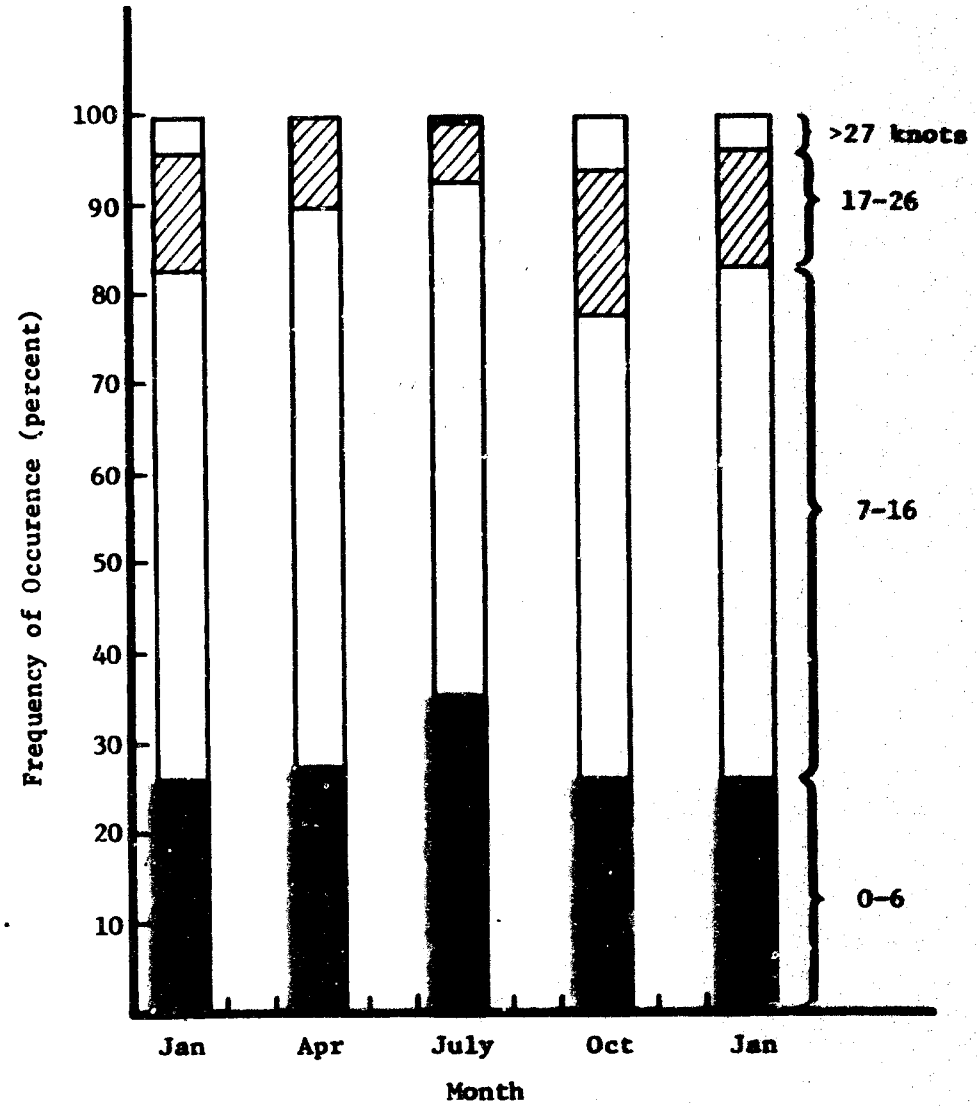
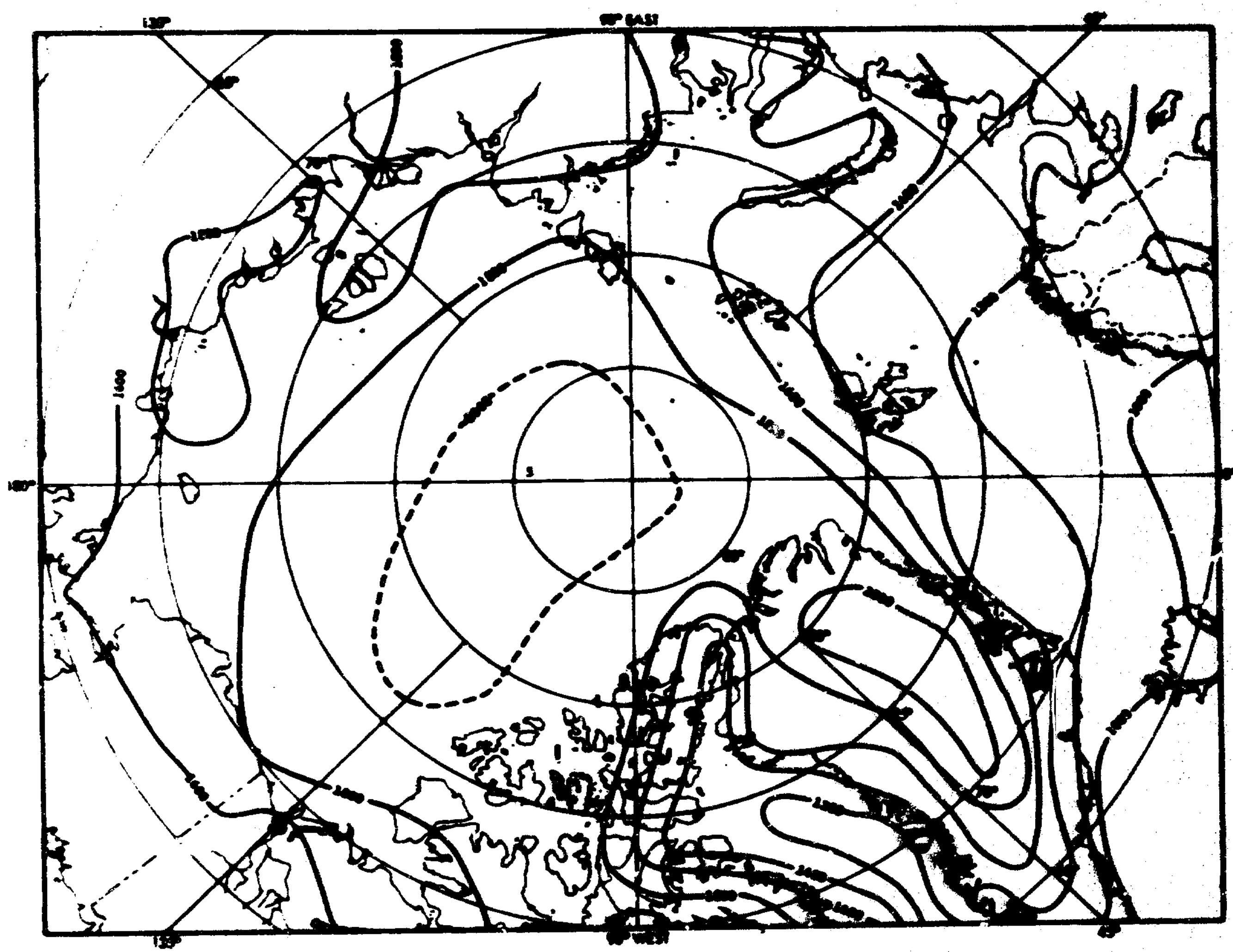


Figure 7-27: COMPOSITE ICE ISLAND SURFACE WIND SPEEDS



REF: U.S. NAVY MARINE CLIMATIC
ATLAS OF THE WORLD
VOL. VI ARCTIC OCEAN NAVWEPS
50-1C-533

Figure 7-28: MEAN WIND CHILL INDEX FOR COLDEST MONTH

30 to 50% of each month, with slightly lesser frequencies occurring in the summer months. However, the frequency of precipitation is not representative of the amounts since generally only a traco of precipitation (<0.005 inch, liquid equivalent) is measured. Examples of precipitation amounts taken from the records of T-3 indicate quantities on the order of 0.05 to 0.15 inch (water equivalent) as maxima occurring in 24 hours and monthly totals varying between 0.1 and 0.7 inch (Reference 7).

Snow and ice crystals occur throughout the year, with some instances of rain and drizzle reported during the summer months. Snowfalls of 4 to 6 inches at one time have been reported, but commonly snowfalls less than 1 inch occur.

For the midseasonal months of the T-3, Arlis II, and NP-2 records surveyed in this study, the average number of days of a trace of greater precipitation were determined, as shown in Table 7-8. It is apparent from the wide range of precipitation occurrences that have been observed, it can be concluded that there is little seasonal variation in this parameter.

Table 7-8: AVERAGE DAYS OF PRECIPITATION, TRACE OR GREATER, ICE ISLANDS

	January	April	July	October
Average	20	14	16	21
Range	6–29	3–28	5–26	3–30

7.3.7 Relative Humidity

Relative humidity observations are reported in some of the ice island records. Because of the cold temperatures prevailing in the arctic, the measurement of relative humidity is very inconvenient requiring periods up to 1/2 hour for proper evaluation. Most of the observations from NP-2 indicate that relative humidity varies between 80 and 100% with no values less than 75 reported, and most observations showing it to be greater than 90%. These values may be compared with the mean monthly relative humidities stated for some fixed land stations as shown in Table 7-9 (Reference 3).

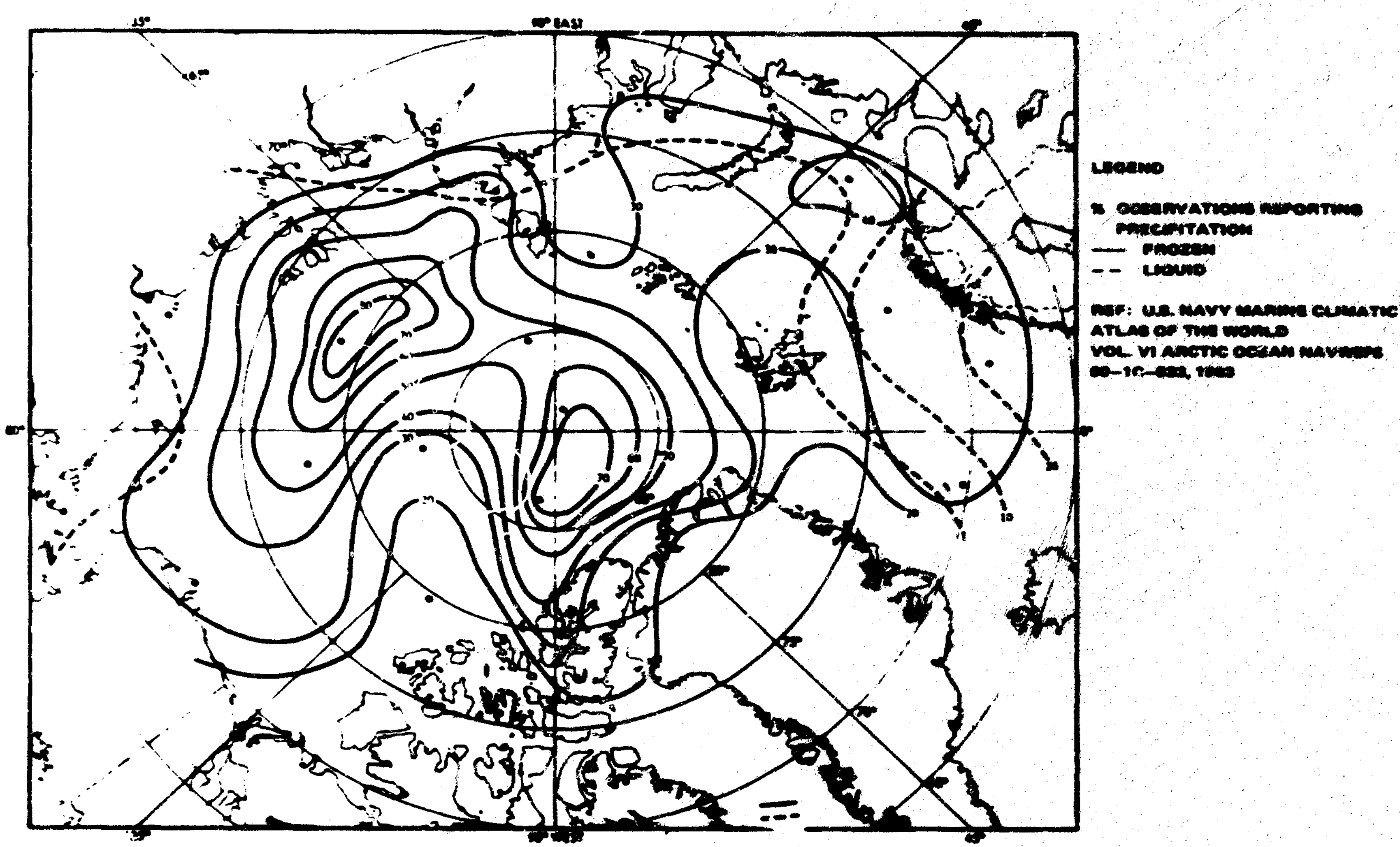


Figure 7-29: PRECIPITATION JANUARY

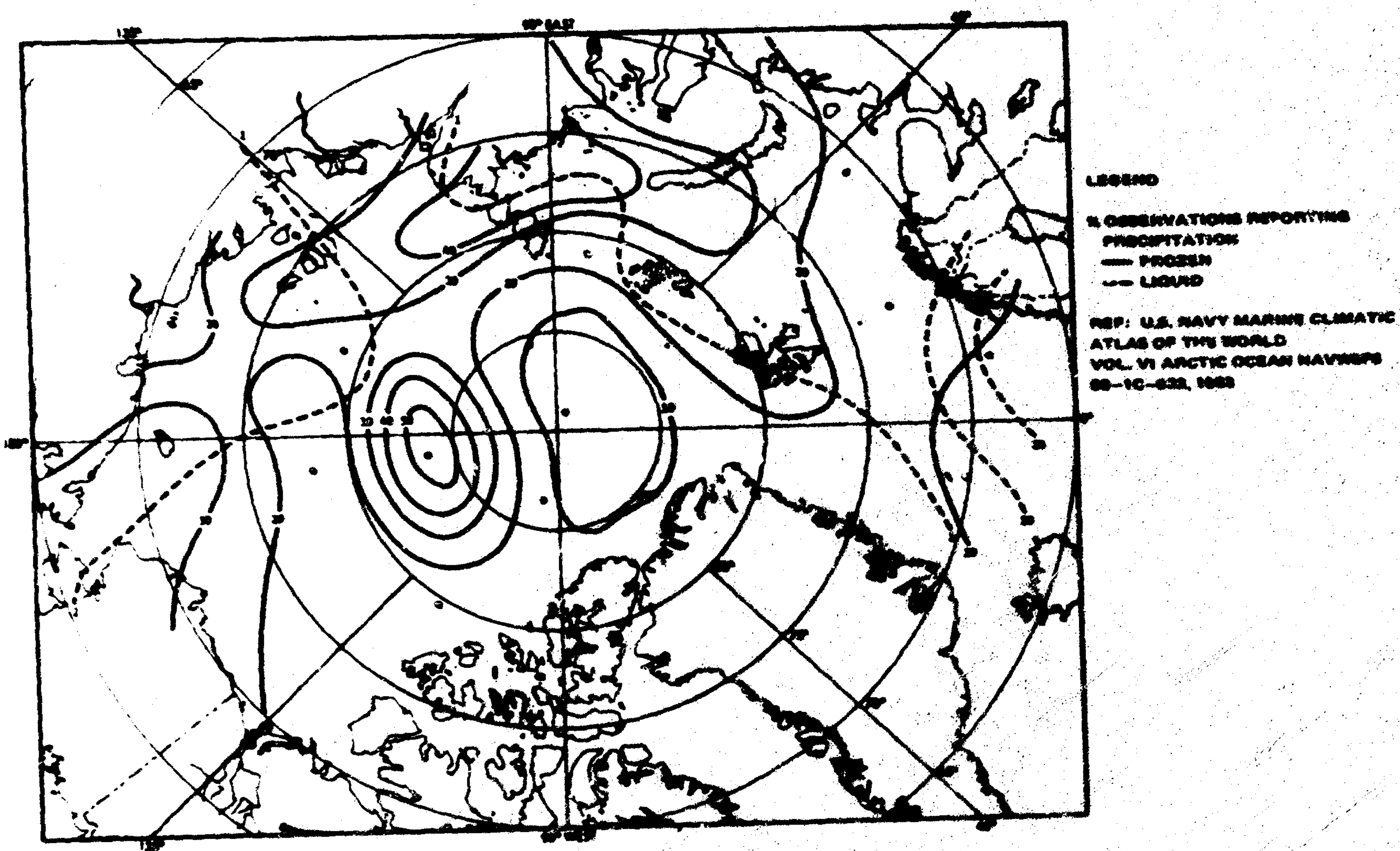
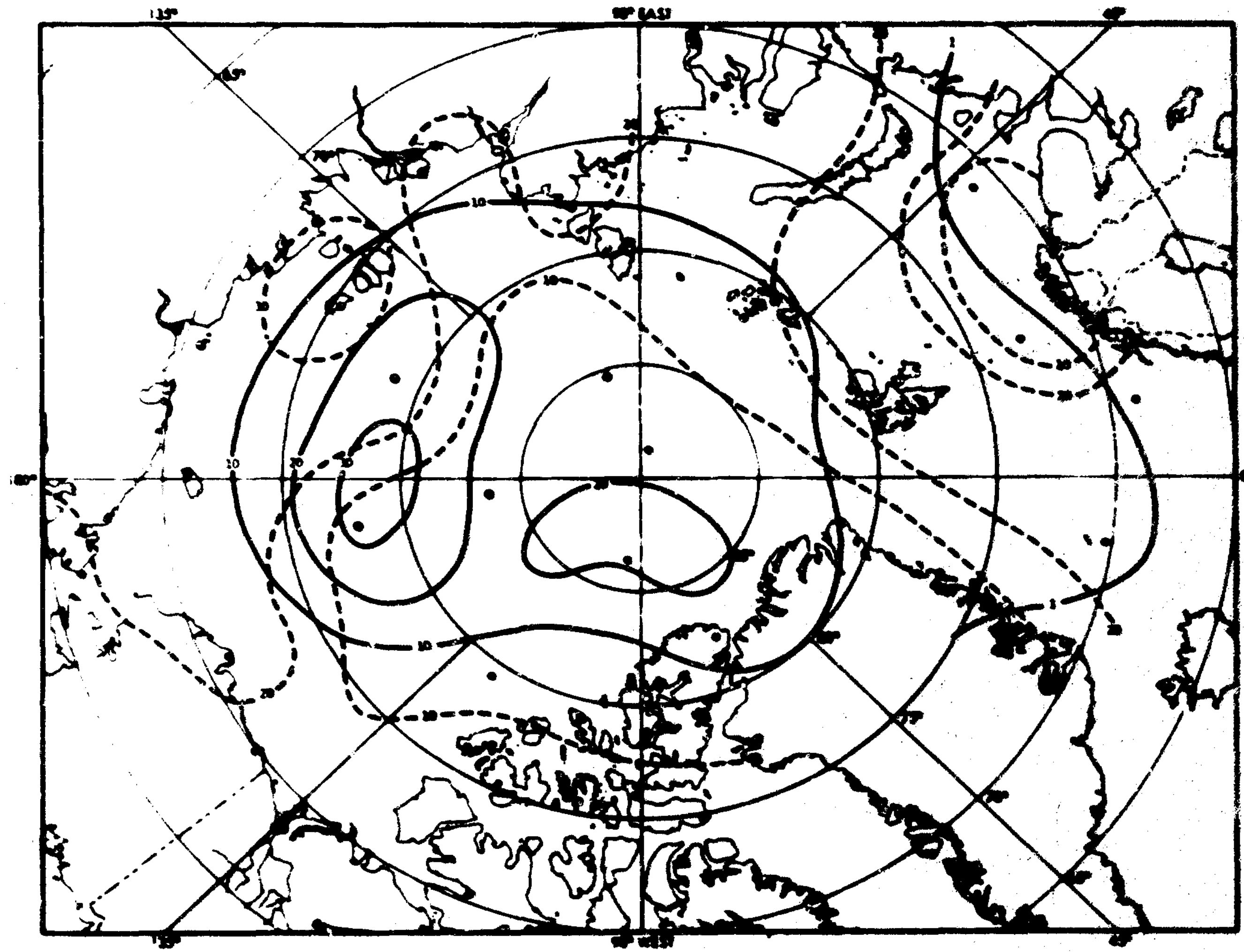


Figure 7-30: PRECIPITATION APRIL



LEGEND

% OBSERVATIONS REPORTING PRECIPITATION
— FROZEN
-- LIQUID

REF: U.S. NAVY MARINE CLIMATIC ATLAS OF THE WORLD VOL. VI ARCTIC OCEAN NAVWEPS 50-1C-533, 1963

Figure 7-31: PRECIPITATION JULY

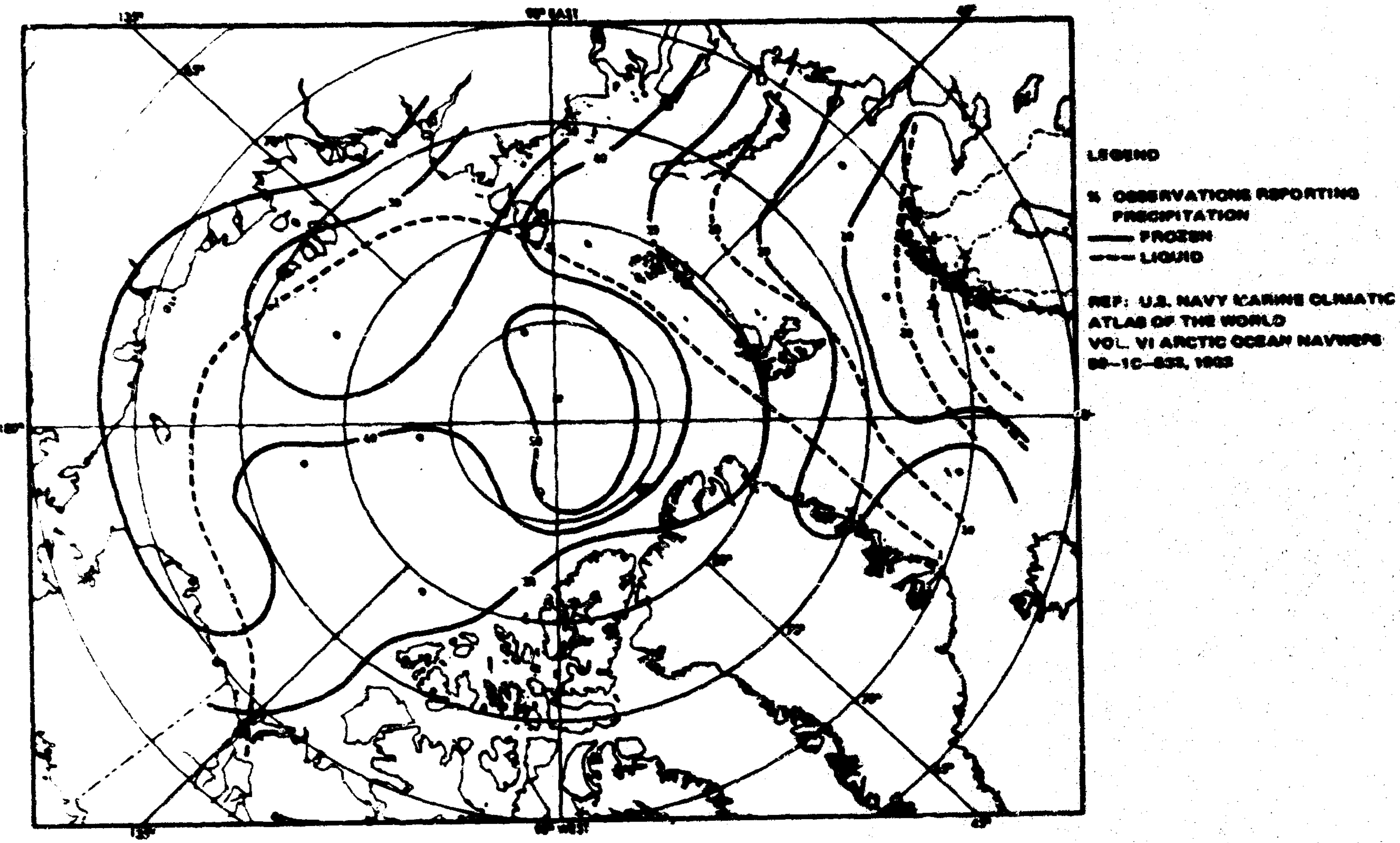


Figure 7-32: PRECIPITATION OCTOBER

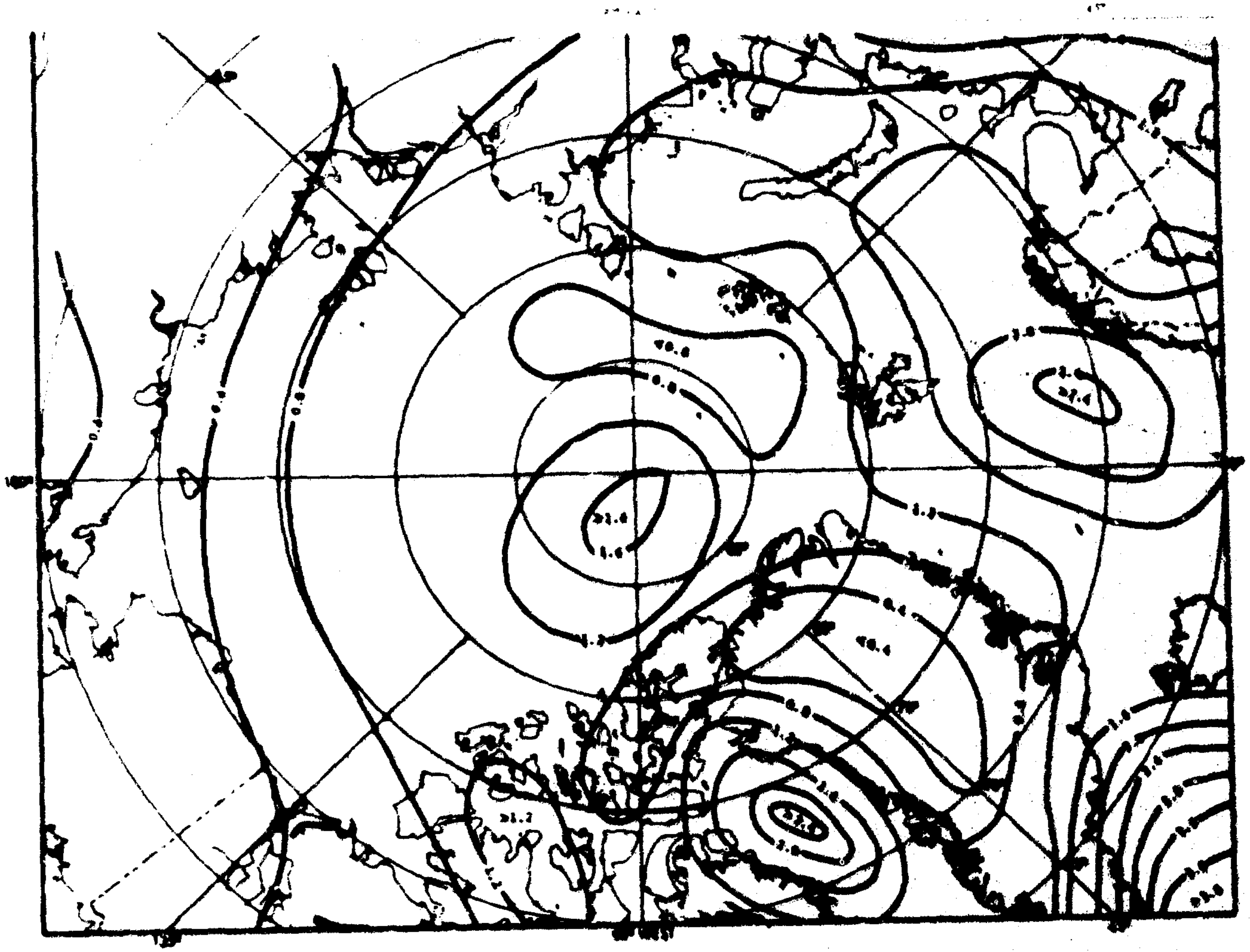
Table 7-9: MEAN MONTHLY RELATIVE HUMIDITY AT FIXED LAND STATIONS

	Jan.	April	July	Oct.
Alert	65	65	81	75
Nord	74	70	79	81
Peary Land	77	73	69	73
Thule	61	64	75	73
Cape Zhelenya	90	89	92	86
Ostrov Vrangelyya	86	84	75	86
Grønfjorden	81	75	78	80
Point Barrow	68	76	90	87

7.3.8 Synoptic Circulation Patterns (Storm Occurrence)

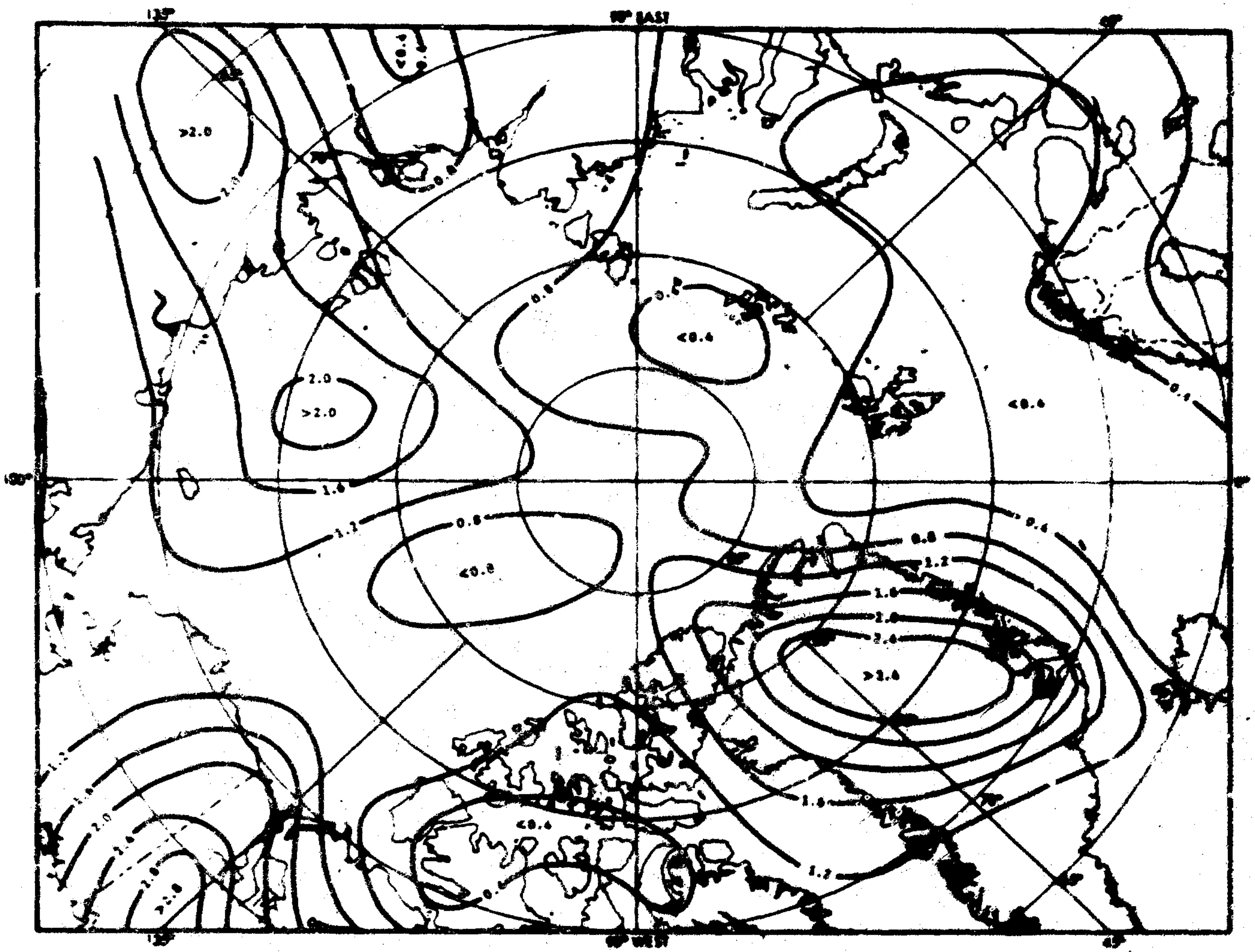
The frequency of occurrence of synoptic weather activity (cyclonic and anticyclonic pressure systems) have been analyzed by two researchers; Keegan considered 15 winter months between 1952 and 1957, and Reed and Kunkel studied five summer sequences between 1952 and 1956. The detailed analyses performed in these two references are considered representative of the best available information on arctic circulation patterns at this time. The data in the remainder of this section is taken from these two sources (References 8 and 9).

Figures 7-33 and 7-34 show the frequency of occurrence of cyclones and anticyclones in winter north of 60°N per 100,000 square miles, according to Keegan. Winter months were December to February for his study. The data were derived from daily weather analyses, including data from T-3, NP-3 and NP-4. A maximum of cyclonic occurrence appears in Baffin Bay, and a second maximum northwest of Norway. A slightly lesser maximum is noted to the western side of the pole over the ice. It is stated that the mass of Greenland acts to divert cyclones approaching from the south or southwest so that they pass up the western coast to stagnate in Baffin Bay or turn eastward across Iceland and north of Norway. It is further observed that eastern Siberia and western Alaska have a pronounced minimum of cyclones and that few cyclones from the Pacific Ocean



REF: (KEEGAN, 1958)

Figure 7-33: FREQUENCY OF CYCLONES IN WINTER %/100,000 SQ MI



REF: (KEEGAN, [illegible])

Figure 7-34: FREQUENCY OF ANTICYCLONES IN WINTER %/100,000 SQ MI

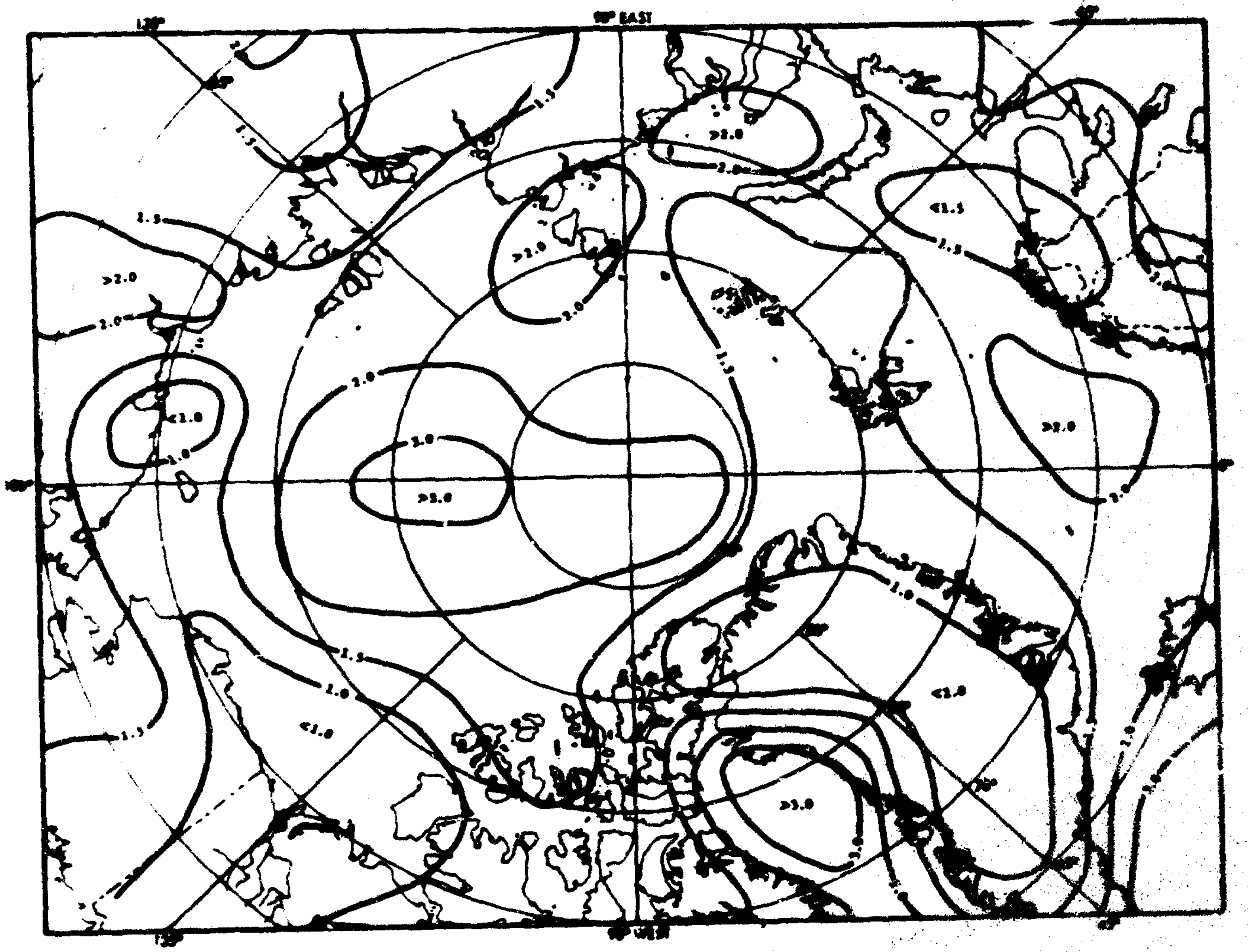
pass north into the arctic. Over the pole itself considerable variation in synoptic weather is reported, and Keegan uses an example of a 1,050-mb anticyclone, which had persisted over the pole for almost 3 months and which in 3 days had moved to permit a 1,000-mb cyclone to take up this position. This sudden reversal of climatic regime is not uncommon in high latitudes, and is further supported by the example given in Section 7.3.2.

Anticyclones are dominant over Greenland, eastern Siberia and eastern Alaska. In general, anticyclones follow less definite courses with relatively slow movement. The anticyclones over Siberia are considered by Keegan to be the strongest and coldest of all. These systems stagnate for long periods of time over eastern Siberia. On occasion relatively small intense anticyclones develop north of Wrangel Island as indicated by the maximum frequency in Figure 7-34. The frequency maximum in Alaska is the result of intrusions of Siberian and north Pacific high-pressure systems. These systems can remain in this location for many days.

The study of Reed and Kunkel presents a comparable survey of summer circulation patterns over the arctic and Figures 7-35 and 7-36 show the frequency of cyclonic and anticyclonic systems according to their analysis. These frequencies are based on zones of analysis of 100,000 square kilometers (slightly smaller areas than those used by Keegan) for the months of July through September. In summer, cyclones appear most frequently in Baffin Bay, southeast of Greenland, and northeast of Norway, as is generally the case of winter cyclonic activity. In addition, a maximum of occurrence appears near the dateline between 80° and 85°N. The latter center influences the entire Arctic Basin, and is therefore consistent with the dominance of clouds during this period (Reference 9).

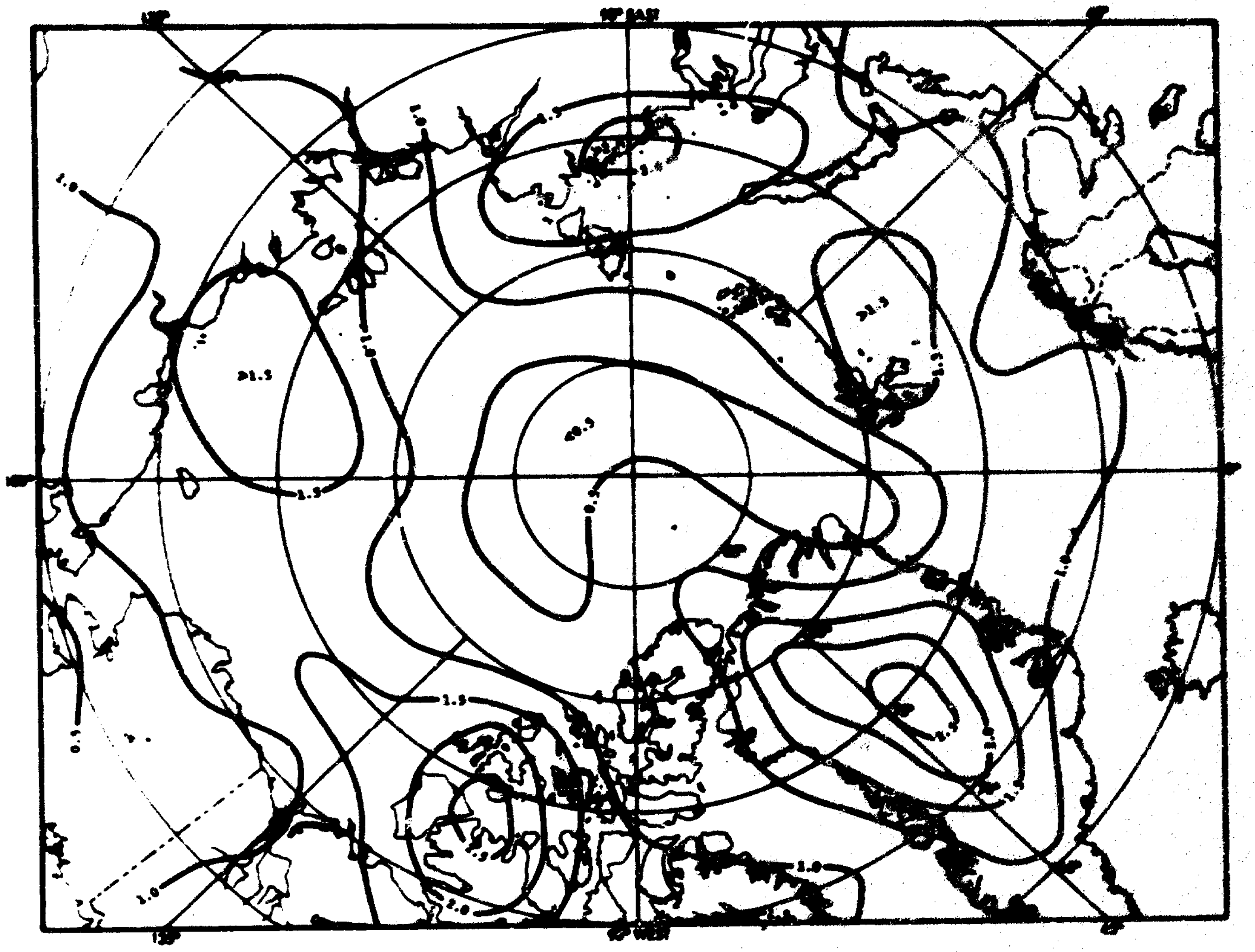
The frequency of summertime anticyclones shown in Figure 7-36 coincides with the zones of absence of cyclones and are all located near 75°N latitude having five primary centers: Canadian Archipelago, Greenland, between Spitzbergen and Novya Zemlya, and two centers north of Siberia. Over the pole itself, anticyclones have a frequency of occurrence of less than 0.5, which is contrary to some previous arctic studies in which semipermanent polar anticyclonic activity was assumed.

Reed's analysis provides a further insight into the changeability of synoptic systems in the arctic region, which is referred to as the "rate of alternation." The rate of alternation is defined as the ratio of cyclone-to-anticyclone frequency or anticyclone-to-cyclone frequency, such that the ratio is less than 1. The summer analysis of rate of alternation is shown in Figure 7-37 where the shaded area designates regions of nearly equal frequency of occurrence, i.e., high rates of alternation. The clear zones contained within the shaded area reflect the dominance of anticyclones in these positions, while the areas surrounding the shaded areas are predominantly cyclonic activity. In a sense, the rate of alternation is a measure of the persistence of these synoptic systems.



REF: REED & KUNKEL, [illegible]

Figure 7-35: FREQUENCY OF CYCLONE CENTERS IN SQUARES OF 100,000 KM^2 JULY - SEPTEMBER



REF: REED & KUNKEL, 1960

Figure 7-36: FREQUENCY OF ANTICYCLONE CENTERS IN SQUARES OF 100,000 KM^2 JULY - SEPTEMBER

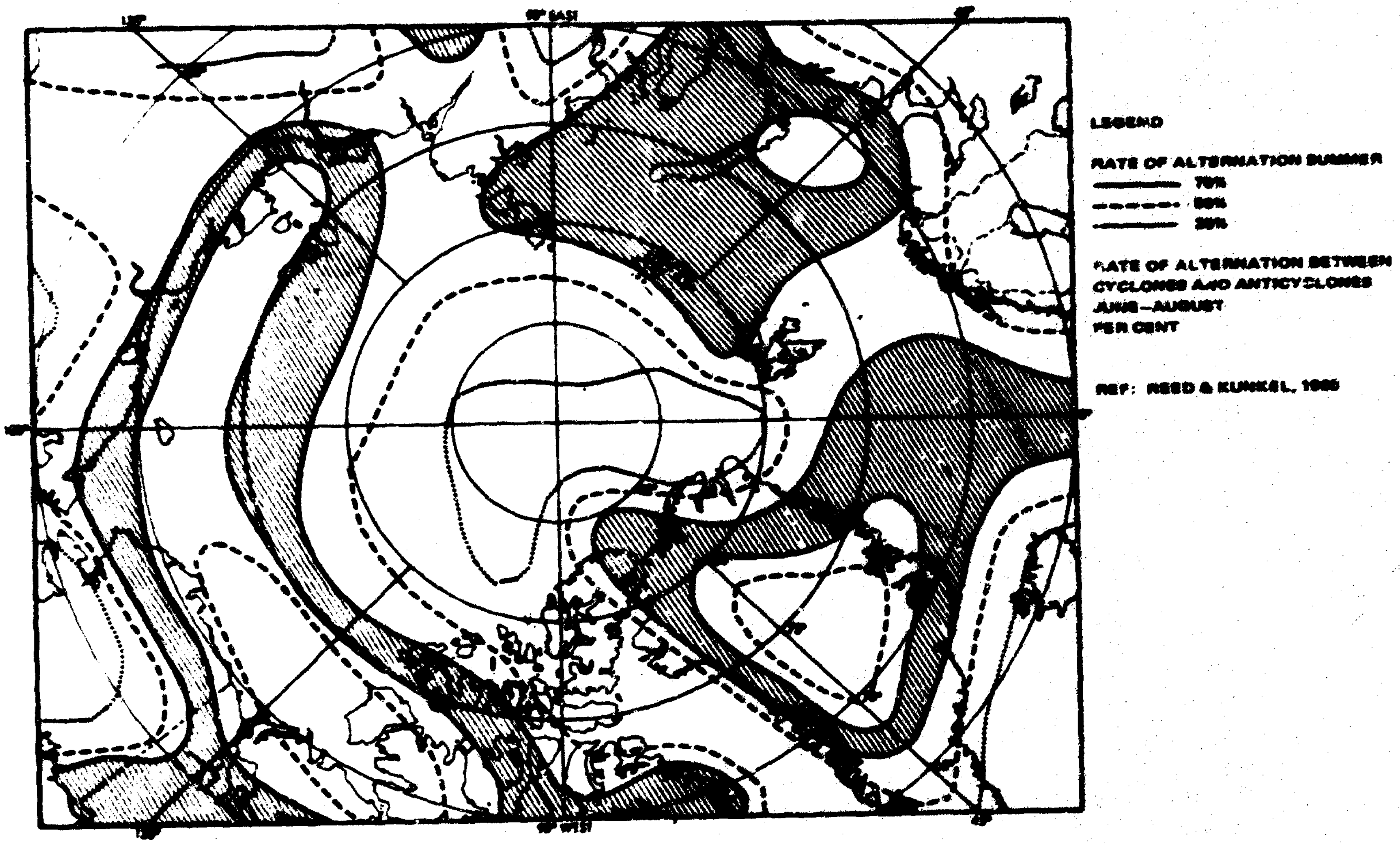


Figure 7-37: RATE OF ALTERNATION BETWEEN CYCLONES AND ANTICYCLONES JUNE - AUGUST

An analysis of the frequency of surface fronts is also provided by Reed and Kunkel. It shows that the major frontal frequencies lie south of the Arctic Basin (south of 70°N). Less than 20% of fronts occur over the polar ice pack, according to this study.

7.4 RELIABILITY

Reliability of information gained in any climate analysis is determined by the period of record of the stations and the number of stations used in developing the analysis. In the arctic region, both "yardsticks" are poor: the drifting ice stations have irregular, generally short periods of records (T-3 is an exception), and the number of stations at any one time was two, or three at best. Thus, an analysis based on ice island data alone does not truly represent the climate.

The purpose of this study has been to describe the meteorological environment over the central Arctic Basin, but in order to do this it has been necessary in many instances to expand the area of concern to include the surrounding permanent land stations. These latter stations have periods of continuous records from 2 to greater than 10 years. Even these lengths of record are insufficient to fully evaluate the long-period trends in weather variables. Where possible, however, data for different years at similar locations have been compared. Based on the degree of similarity, a conclusion can be made on the representativity of the data sample.

The fact that the arctic ice lacks significant terrain features aids in extrapolation of the results from one location to another. Far greater caution must be used in the zones bordering the central ice pack where influences of large open water bodies may be considerable.

It is believed that the trends of individual variables presented here are representative of the basic conditions observed within the Arctic Basin. The only other source of comparable climatic information is the U. S. Navy Marine Climatic Atlas, Vol. VI. In general, the variables considered agree with the few instances of similar studies. The information is presented herein in a manner that supplements, as well as includes, data presented in the atlas (Reference 7).

The present study is deficient in data from the eastern (USSR) side of the ice pack. Few drifting stations have penetrated these zones, and the few that have touched this region have been Russian stations for which data records are not available. In the absence of records of this rather large and important component of the Arctic Basin, the conclusions are assumed to apply.

7.5 REFERENCES

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2) U. S. Naval Weather Service (1967), World-Wide Airfield Summary Vol. IV, Canada, Greenland, Iceland.

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4) --------(1960), Extent of Clouds Over Arctic Seas and Central Arctic USSR, Translation by Office of Technical Services, OTS: 60-31, 036.

5) Belmont, A.D. (1959), Upper Air Temperatures, 1952-1954, Geophysical Research Papers, No. 63, AFCRC-TR-59-232, Vol. 1.

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8) Keegan, T.J. (1958), "Arctic Synoptic Activity in Winter," Journal of Meteorology, Vol 15, No. 6.

9) Reed, R. J. and E. A. Kunkel (1960), "The Arctic Circulation in Summer," Journal of Meteorology, Vol. 17, No. 5.

7.6 CLIMATOLOGY GLOSSARY

Cloud Types

Altocumulus — Middle-altitude clouds (6,500 to 20,000 feet). White or gray in color, predominantly composed of water droplets. Occur in flaky or flat globular masses, in patches or wavelike masses, to form one or multiple layers. Elements are larger than cirrocumulus with darker shadings in centers. Cloud edges are often iridescent in proper lighting, and thin altocumulus in passing before the sun or moon result in corona formation.

Altostratus	Middle-altitude clouds (6,500 to 20,000 feet). Grey or blue-grey sheet of either uniform or striated appearance. Often spread to cover entire sky, and thicken occasionally to obscure the sun. Do not produce a halo. Low altostratus distinguished from stratus or nimbostratus as being less dark in appearance. Precipitation, often steady and continuous but rarely heavy, is frequent.
Cirrus	High-altitude clouds (>20,000 feet). White patches or banded clouds, often "fibrous" composed of ice crystal particles. Less continuous than cirrostratus. Halo phenomenon when sun shines through cirrus clouds.
Cirrocumulus	High-altitude clouds (>20,000 feet). White small flakes or very small globular cells, often arranged in bands (clouds forming a "mackerel sky"). Most common cirroform cloud. May contain some supercooled water droplets.
Cirrostratus	High-altitude clouds (>20,000 feet). White or whitish-appearing sheet often covering greater portion of entire sky, and particularly obvious for appearance of halo phenomenon. Thin cirrostratus at night may not be apparent except for occurrence of a halo. Edges of cirrostratus sheets often contain cirrus clouds. Precipitating ice particles give fibrous appearance on occasion.
Cumulus	Clouds of vertical development generally having low bases. Cumulus clouds are individual masses of white, with darker shading on bottom. Composed of small water droplets sometimes providing light precipitation. Where development is limited, these clouds are referred to as fair-weather clouds. Under conditions of continuing energy supply, cumulus clouds develop into cumulonimbus.
Cumulonimbus	Clouds of large vertical development, often very dark at base and brilliant white at top. Commonly related to thunderstorms and in mature stages of development produce heavy shower-type rain. When these clouds build to high altitudes, they often provide a source of cirrus or cirrostratus clouds and, with sufficient wind, form anvils of spreading cirroform cloud.
Nimbostratus	Low-level clouds (<6,500 feet). Very dark grey continuous cloud layer orally precipitating steady rain or snow. Nimbostratus most often develop as thickening and lowering altostratus.

Stratus Low-level clouds (<6,500 feet). Grey, continuous appearance having a uniform base. Produces drizzle or light rain on occasion. Resembles and often develops from fog that has lifted from the surface.

Stratocumulus Low-level clouds (<6,500 feet). Grey or whitish appearing cellular clouds whose elements generally become connected. Discernable from cumulus in that both bases and tops are generally uniform in height. Rarely cause precipitation, and often develop through the lifting of a stratus cloud layer. Cloud elements larger than those of altocumulus.

Descriptive Terms

Synoptic Weather Analysis An analysis of meteorological variables made periodically, providing an overall picture of features having scales of hundreds to thousands of miles.

Cyclone A relatively low-pressure system whose circulation is counterclockwise in the Northern Hemisphere. Commonly, a cyclone has a scale a few hundreds of miles and characteristically contains low clouds, clouds of vertical development, strong winds, precipitation, and generally bad weather. Cyclones usually move from west to east and are transient-type features.

Anticyclone A relatively high-pressure system whose basic circulation pattern is clockwise in the Northern Hemisphere. Larger and slower systems than are cyclones, they remain stationary over extended periods of time. Characterized by light and variable winds, clear skies, occasional fogs, and generally good weather.

Temperature Inversion A departure from the usual decrease of temperature with increasing height. Commonly taken to be any vertical gradient of temperature from isothermal (no change with altitude) to increase in temperature. If the base of the inversion layer is the surface, it is known as a surface inversion. The top of the inversion is the height of maximum temperature.

Stability (Static or Hydrostatic) The condition of the atmosphere with reference to vertical displacements. The criterion for stability is that a parcel of air displaced upward or downward be subjected to a buoyant force opposite to its displacement.

8.0 ARCTIC OCEANOGRAPHY

8.1 INTRODUCTION

It is difficult, if not impossible, to separate the oceanographic characteristics of the Arctic Ocean from the dominating ice cap that covers the water; however, for purpose of this study the oceanographic environment is considered to be all aspects of the ocean other than the ice.

As with most other aspects of the arctic environment, knowledge of the oceanographic environment is severely limited by lack of both synoptic and geographic coverage. Unlike data on the ice pack, however, the majority of measurements have been obtained by sensors and are, therefore, less subjective. No attempt has been made to make this section an exhaustive compilation of the oceanographic characteristics of the arctic; rather, effort has been concentrated on those aspects of the environment that appear to be most significant to system operation.

8.2 DATA SOURCES

The primary source of compiled data on arctic oceanography is the Oceanographic Atlas of the Polar Seas which, while some 12 years old, remains the best and most reliable source for such information as sea and swell conditions, tides, currents, temperature, and salinity. In addition to this basic source the U. S. Navy Oceanographic Office has supplied updated information on bathymetry, sea and swell along the arctic coast of Alaska, and sound propagation data. Additional sound propagation data was obtained from AC Defense Research Laboratories, and A. R. Milne of the Defence Research Establishment---Pacific (Reference 4).

8.3 OCEANOGRAPHIC DATA

8.3.1 Bathymetry

Bathymetric data for the central arctic in the area covered by permanent ice pack is very sparse, and detail for large areas is lacking. Soundings in the basin have been obtained primarily from floating ice stations, traverses by icelocked ships, ice breakers operating in marginal areas during the summer, and during the last 10 years by submarine under-ice traverses. Except for soundings obtained by submarines, the locations of soundings have been subject to the vagaries of the pack movement. Greater bathymetric detail is available for the shallower shelf regions that become navigable for surface vessels during the summer. However, data is sparse in some areas of the continental shelf, particularly along the North American continent and Greenland.

Depths exceeding 1,000 fathoms occur over the major portion of the deep basin except for the Lomonosov Ridge, (Figures 8-1 through 8-3). Depths exceeding 2,000 fathoms have been reported over a small portion of the North Canadian Basin near the Lomonosov Ridge, over most of the North Eurasian Basin, and the Greenland Basin.

The Lomonosov Ridge appears to be extremely rugged with steep slopes common. Widths are 20 to 40 miles. Over the ridge, depths generally are less than 1,000 fathoms. Beal reports that profiles obtained by submarines show the crest of the Ridge to be between 600 and 656 fathoms. North of Greenland, a minimum depth of 410 fathoms was found. A minimum depth of 399 fathoms was reported north of Franz Josef Land, 86°50'N, 61°51'E, by Russian observers (Reference 13).

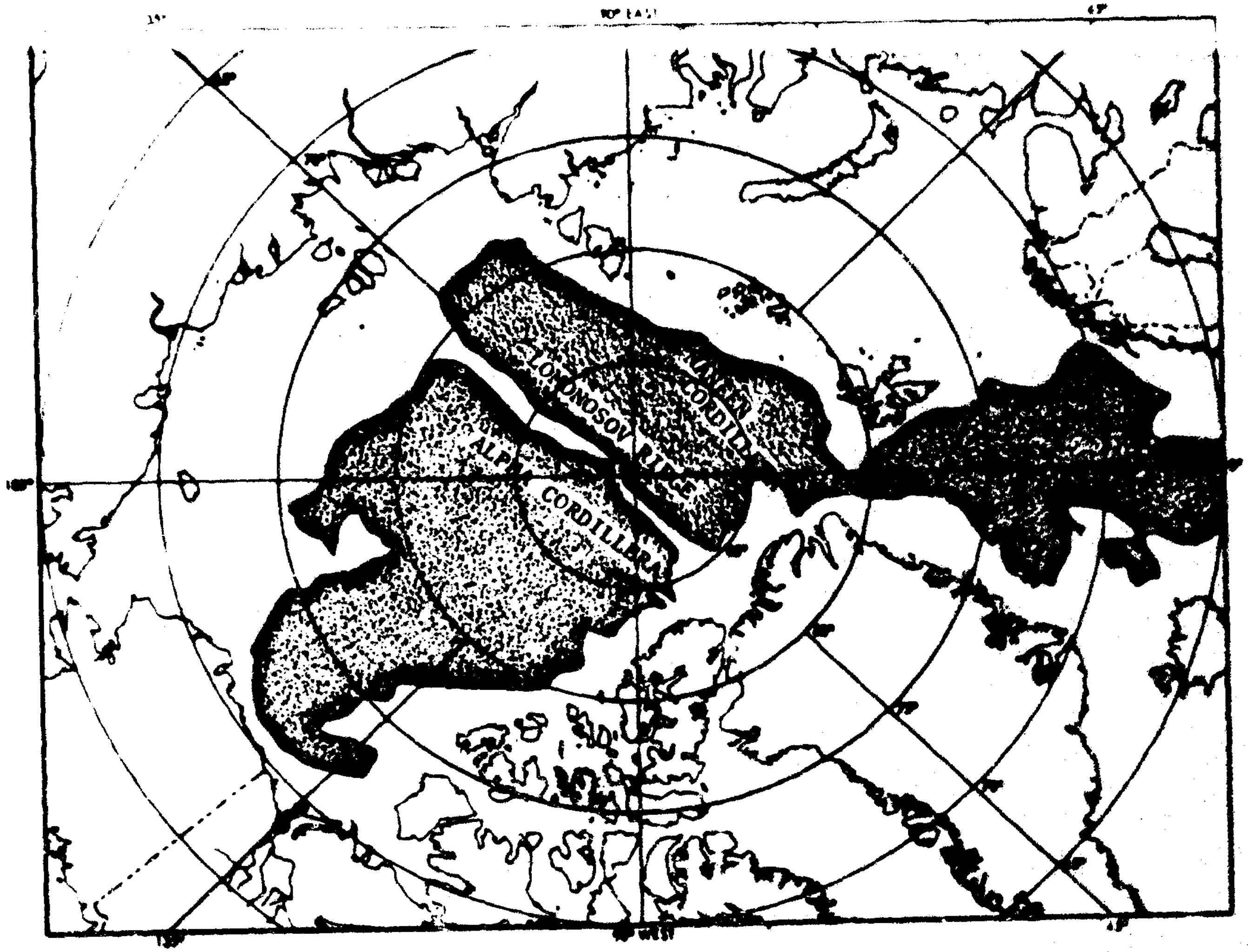
In addition to the Lomonosov Ridge, the Alpha Cordillera and the Nansen Cordillera further divide the basin. The Alpha Cordillera is a wide mountain range with a minimum width of about 160 miles. This range extends from the continental slope of the Canadian Archipelago roughly parallel to the Lomonosov Ridge to the continental slope of Asia. The minimum known depth is somewhat greater than 500 fathoms close to the slope off Ellesmere Island. In the middle part of the basin, the depths are in excess of 1,000 fathoms. On the opposite side of the Lomonosov Ridge, the Nansen Cordillera extends from the passage between Svalbard and Greenland to the continental slope off the Lena River. This ridge is throught to be an extension of the Mid-Atlantic Ridge. The width of the Nansen Cordillera is roughly 50 miles and known minimum depths exceed 1,000 fathoms (References 2, 3, 5, 6).

The three mountain ranges divide the deep Arctic Basin into four sub-basins. Each of these sub-basins is approximately 2,100 fathoms deep and is floored by plains with little relief.

8.3.1.1 Chukchi Sea

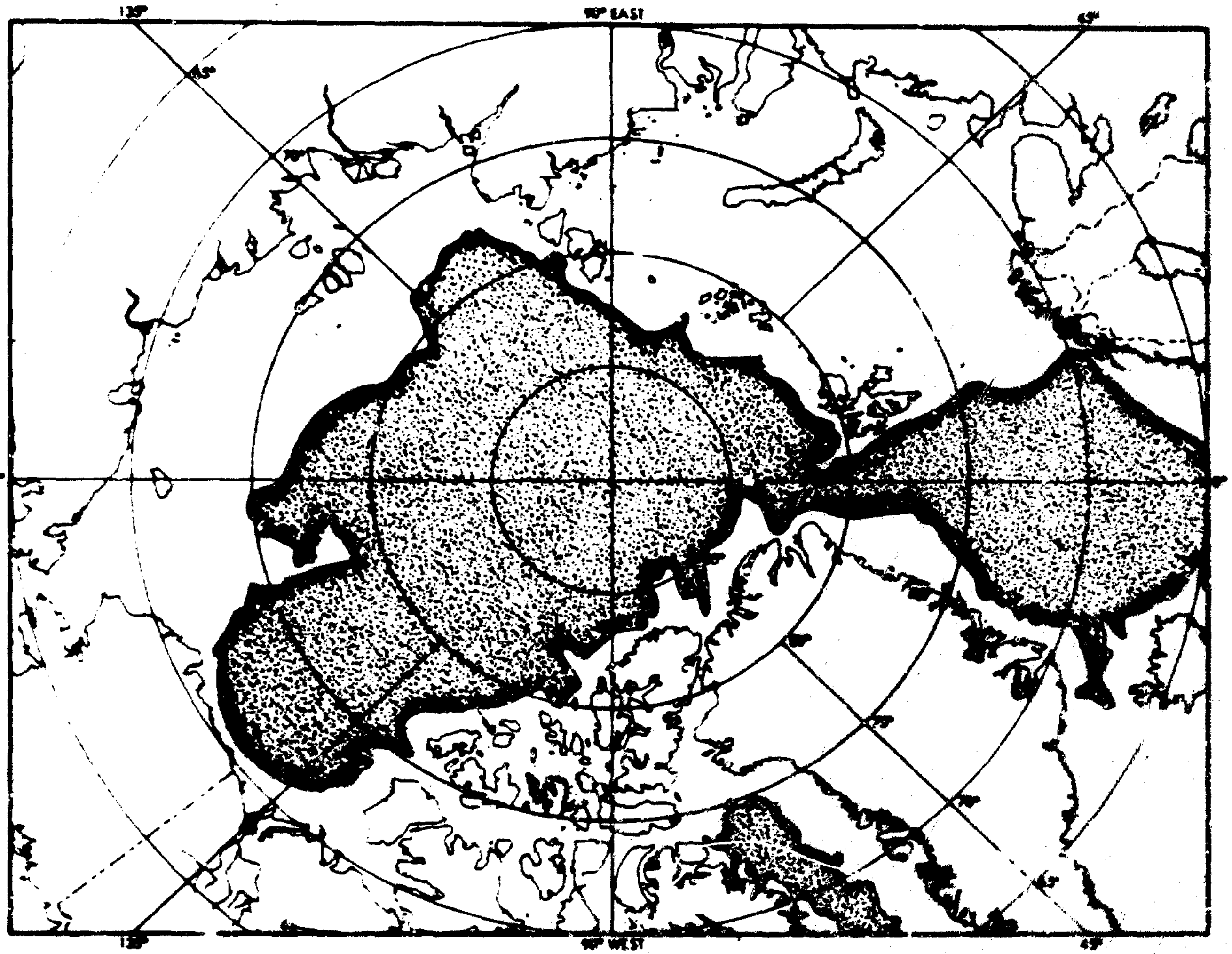
Bathymetry of the Chukchi Sea (Figure 8-4) is relatively well known as a result of soundings by icebreakers during the summer and autumn months and by sumbarine traverses. The area has unusually low relief. Water depth is less than 30 fathoms over nearly all of the area and less than 20 fathoms in a rather broad belt along the Alaskan coast from Cape Prince of Wales to near Point Barrow. The shoal area narrows near Point Hope and Point Barrow. A shoal of less than 20 fathoms also occurs in the central part midway between Wrangel Island and Cape Lisburne. Barrow Canyon provides a deeper access to the main basin.

Reliability of the bathymetry is considered good over most of the area, particularly east of Wrangel Island because of the amount of data and lack of major relief.



SOURCE: HO-706
HO CHART 6781 (C)

Figure 8-1: ARCTIC BASIN BATHYMETRY (DEPTHS GREATER THAN 1000 FATHOMS)



SOURCES: HO-706
HO CHART 6781 (C)

Figure 8-2: ARCTIC BASIN BATHYMETRY (DEPTHS GREATER THAN 500 FATHOMS)

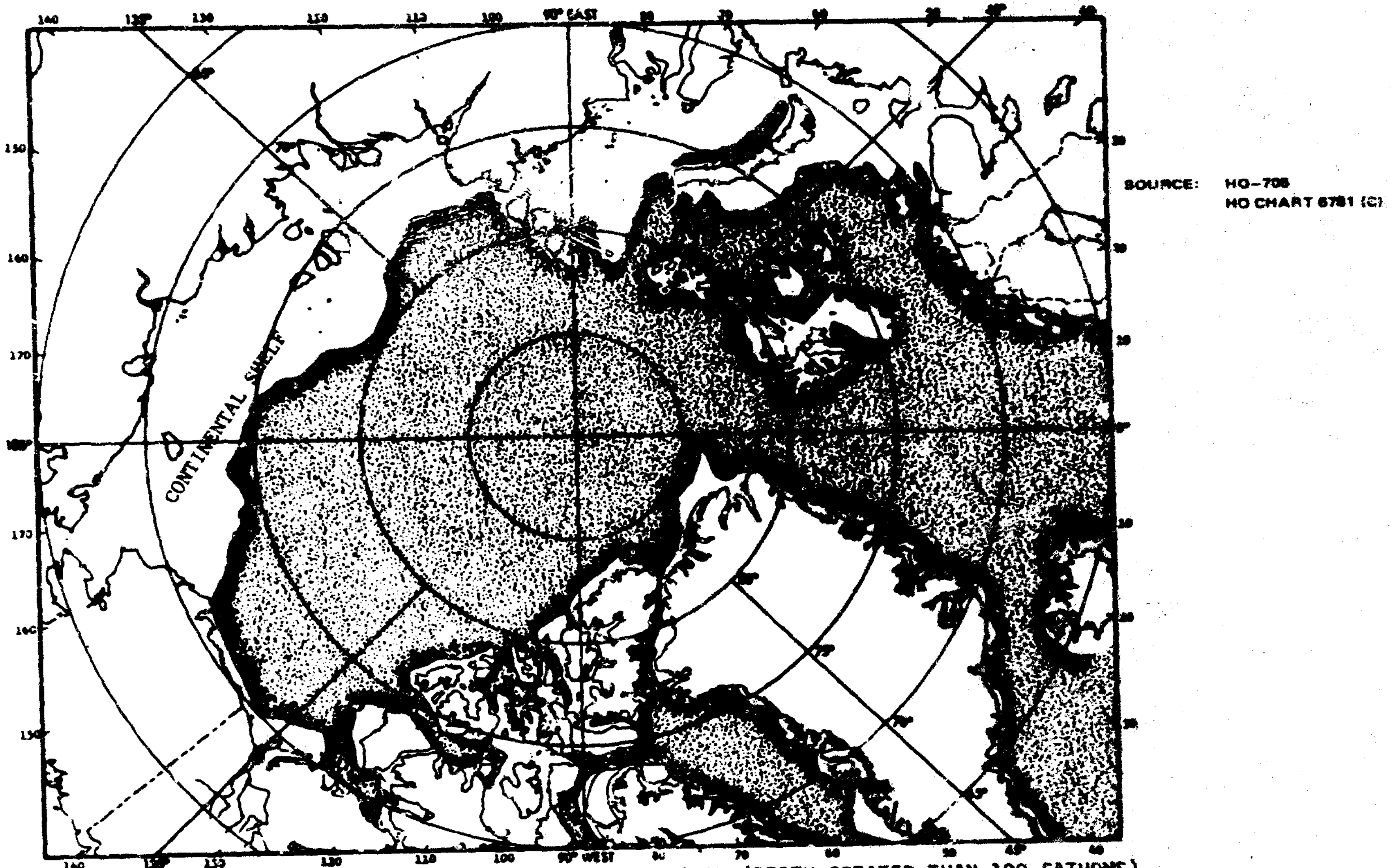


Figure 8-3: ARCTIC BASIN BATHYMETRY (DEPTH GREATER THAN 100 FATHOMS)

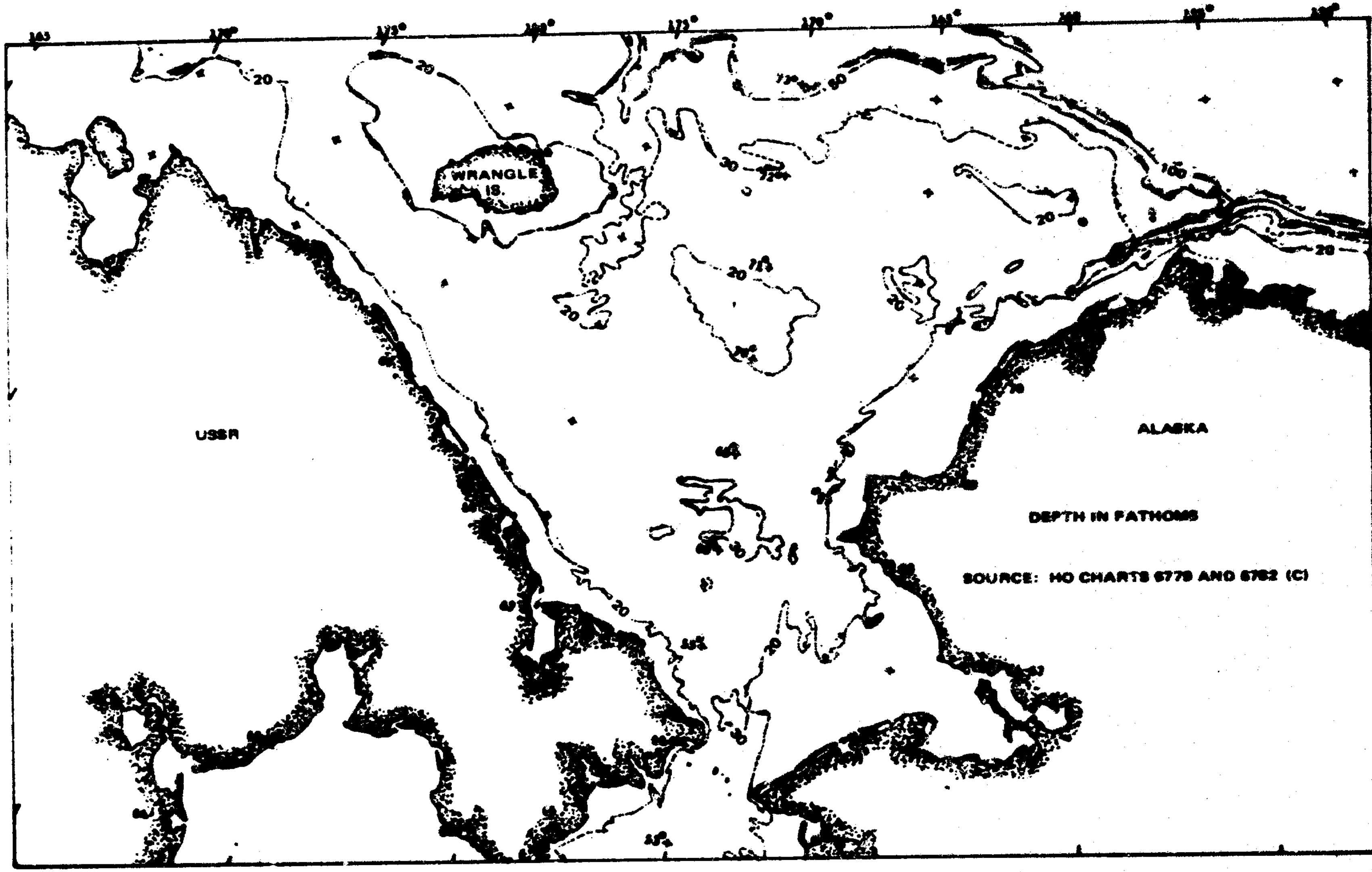


Figure 8-4: BATHYMETRY CHUKCHI SEA

8.3.1.2 East Siberian Sea

The East Siberian Sea (Figure 8-5) lies over one of the broadest shelf areas known. Depths less than 20 fathoms extend 250 miles from the coast and another 100 miles to 30 fathoms. This area is considered one of the flattest known. Delineation of the depth contours is uncertain because of the permanent heavy pack ice and has been reliably established only by submarine traverses in a few places. These are indicated, generally, by somewhat the greater detail shown in the contouring. Reliability of the bathymetry for the area is somewhat near the coast where reduced ice coverage during the summer has made more complete sounding possible. Except as noted, reliability toward the north in the area of permanent pack ice coverage is poor (Reference 5).

8.3.1.3 Laptev Sea

The Laptev Sea (Figure 8-6) also is generally shallow with depths less than 20 fathoms west of the Lena River Delta and between the delta and the New Siberian Islands. Bottom topography is more irregular than the Chukchi. The shelf drops steeply into the basin to the north and toward Severnaya Zemalya and more gently from the New Siberian Islands (Reference 5). Bathymetry out to about 100 fathoms is established with good reliability over most of the area that is not covered by permanent pack ice. Bathymetry near the Lena River Delta may be uncertain in shoal areas.

8.3.1.4 Kara Sea

The bathymetry of the Kara Sea (Figure 8-7) is very irregular with depths ranging between 20 fathoms to over 100 fathoms. Because of the rugged bottom topography many small isolated peaks, some less than 20 fathoms deep, could not be shown on the contour chart at the scale used. The highly variable bottom topography makes this area hazardous for operations even with the detail presently available (Reference 1, 5).

Reliability of the bathymetry is considered good on large scale charts.

8.3.1.5 Barents Sea

Of the seas bordering the Eurasian continent, the Barents Sea (Figure 8-8) is generally the deepest, with depths exceeding 100 fathoms over most of its area. Shallower water of less than 50 fathoms occurs south of Svalbard to latitude 79° and less than 100 fathoms occurs in two large areas, several small isolated peaks, and west of Nova Zemalaya. Depths of 150 to

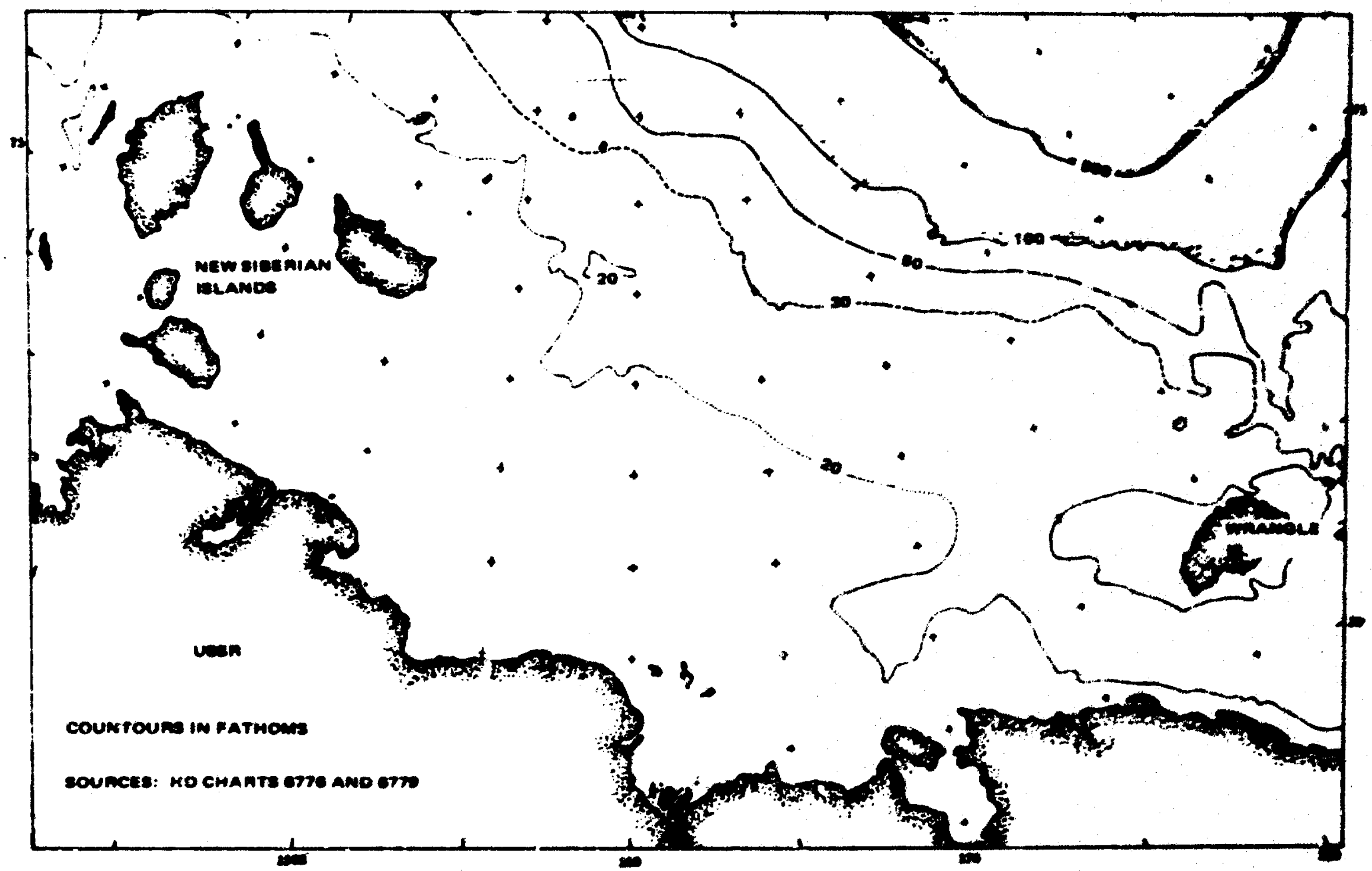


Figure 8-5: BATHYMETRY EAST SIBERIAN SEA

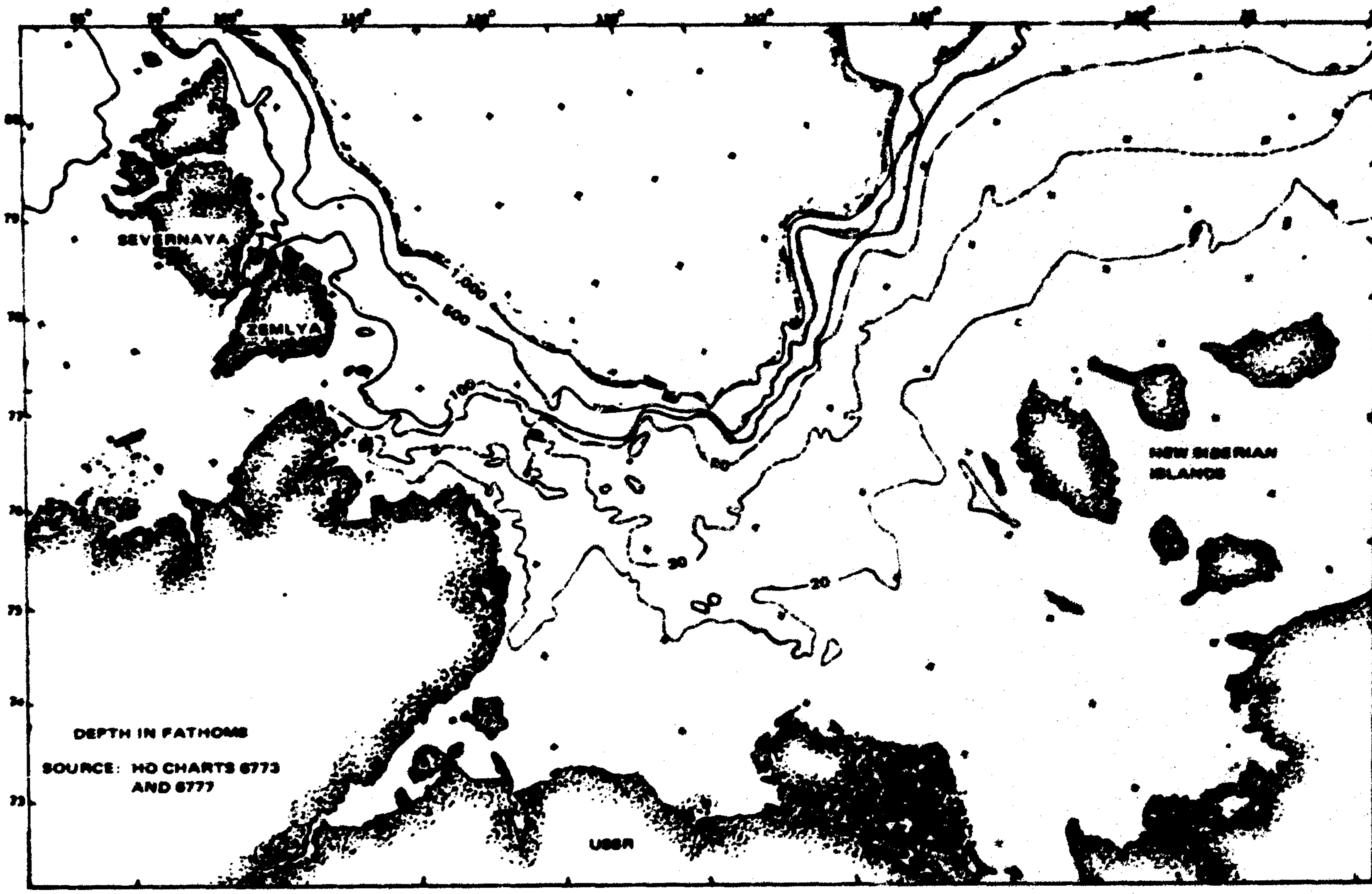


Figure 8-6: BATHYMETRY LAPTEV SEA

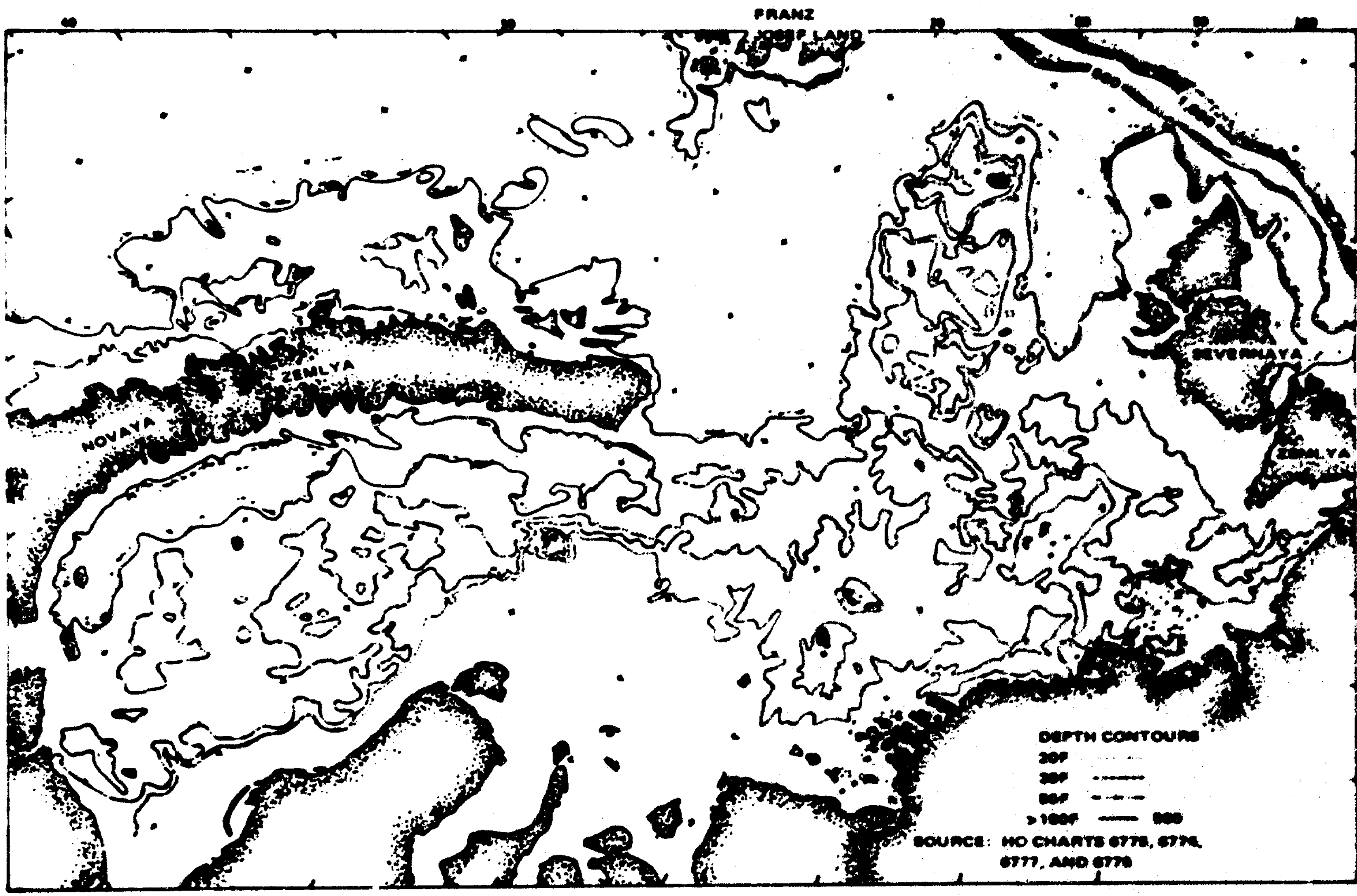


Figure 8-7: BATHYMETRY KARA SEA

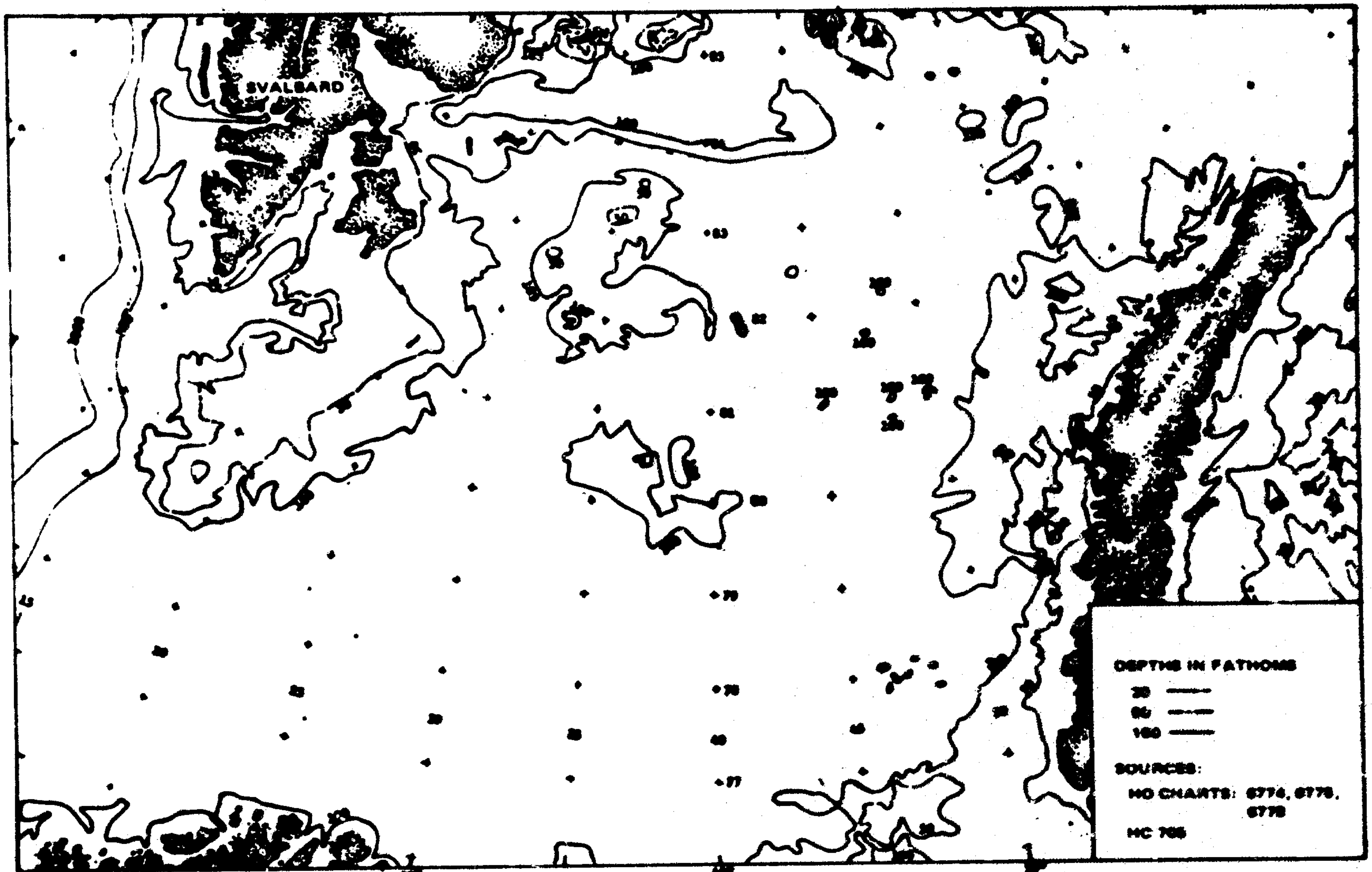


Figure 8-8: BATHYMETRY BARENTS SEA

over 200 fathoms exist over most of the central Barents Sea basin between the shoal area south of Svalbard and the Norwegian coast (Reference 5).

Reliability of the bathymetry is good.

8.3.2 Sea and Swell

Rough to high seas and swell occur almost exclusively in open water areas outside the limit of pack ice and in the outer fringes. They rarely occur in areas of partial ice cover except in areas adjacent to open ocean where conditions permit their formation. Drift ice rapidly damps out seas of shorter wavelength; thus the occurrence of rough to high seas 5 feet or greater decreases rapidly in the vicinity of the pack limits. Penetration into areas of partial cover depends on the ice concentration and thickness, being greater in areas of scattered or thin ice. Young ice is broken by seas and swell, with the amount of comminution greatest near the outer limits. As the ice is broken into smaller brash, penetration may increase with shorter wavelengths damped progressively. Under some conditions swell may penetrate young ice for many miles with accompanying breakup even where coverage may be 10/10 As the swell is damped, the size of the cakes and floes increases (Reference 14).

Seas and swell rarely are observed within the main pack. Small seas may develop in large polynyas, but are limited by the restricted fetch available for generation by wind. Within the pack, even gale-force winds will fail to produce seas in polynyas significant to vehicle operation.

In some areas of limited or insufficient data, the indicated sea and swell isopleths were estimated using wind data as an aid. Lack of observations and the great variability of critical factors does not permit even semiquantitative expression of wave attenuation by ice, and thus wave penetration into the pack.

Seas of 5 feet or greater occur predominantly in the area east of Greenland to Norway, and in the Barents and Kara Seas south of the normal limits of ice coverage. Seas of 5 feet or greater are reported in the Laptev Sea during summer and early autumn. During the summer seas of this height occasionally occur in the southern Chukchi. The area north of Alaska seldom experiences large seas because of the unusually limited extent of open water during the summer. During late summer or early autumn, a sea state of 3 to 4 may occasionally occur in the eastern Beaufort near Amundsen Gulf. On October 21, 1960, a swell sufficient to cause the USCGC Northwind to roll heavily was reported at 70°50'N, 140°30'W. Ice coverage was 10/10. This swell, estimated as about 8 to 10 feet maximum, appeared to have originated

in or near Amundsen Gulf, following gale-force winds from the southeast that continued 24 hours. By October 23, at 71°28'N, 153°33'W, the swell was reported as 2 feet. (References 14, 15 and 16)

Seasonal sea state conditions are shown in Figures 8-9 through 8-12, and seasonal swell conditions are shown in Figures 8-13 through 8-16.

8.3.3 Tides

Although tidal observations are lacking for many areas of the arctic, the information available indicates that the tidal ranges are quite small. The tide range along the entire Arctic Ocean coast of the Canadian Archipelago is about 1 foot, and a similar condition seems to exist along the coast of Alaska, Greenland, and much of the Siberian coast east of the Lena River. Tidal ranges that vary from 1 foot to as high as 8 feet occur in the Khantanga River estuary, and tides from 1 to 3 feet at some locations along the coasts of the Soviet arctic islands. The west coast of Spitsbergen has a tidal range up to about 7 feet in some confined waters.

The Eurasian coast bordering the Barents and Norwegian Seas experiences tidal ranges up to about 9 feet, and more confined areas of the White Sea bordering the Barents Sea may reach 18 feet. Within the Canadian Archipelago the tidal range shows a general increase from the Arctic Ocean southward. In the channels between the more northern islands the maximum range is generally around 3 feet. In the waters directly connected to Baffin Bay the ranges reach 7 to 8 feet, and the waters joining Davis Strait and Hudson Strait show high tidal ranges to as much as 30 feet.

All tides except along the west coast of Alaska are semidiurnal. Those along the west Alaskan coast are diurnal (Reference 14).

8.3.4 Surface Circulation

The general pattern of the Arctic Ocean surface circulation is shown in Figure 8-17. The circulation in the basin is a slow westerly drift forming a large gyral with a clockwise circulation over a major portion of the basin. This movement is exceedingly irregular, however.

The major water influx occurs thorugh the Norwegian and Barents Seas, but during the warm seasons a large quantity of fresh water is added to the basin from the many large river systems that empty into the basin. The major outflow occurs through the Greenland Sea with lesser outflows occurring through the many channels of the Canadian Archipelgo. The marginal

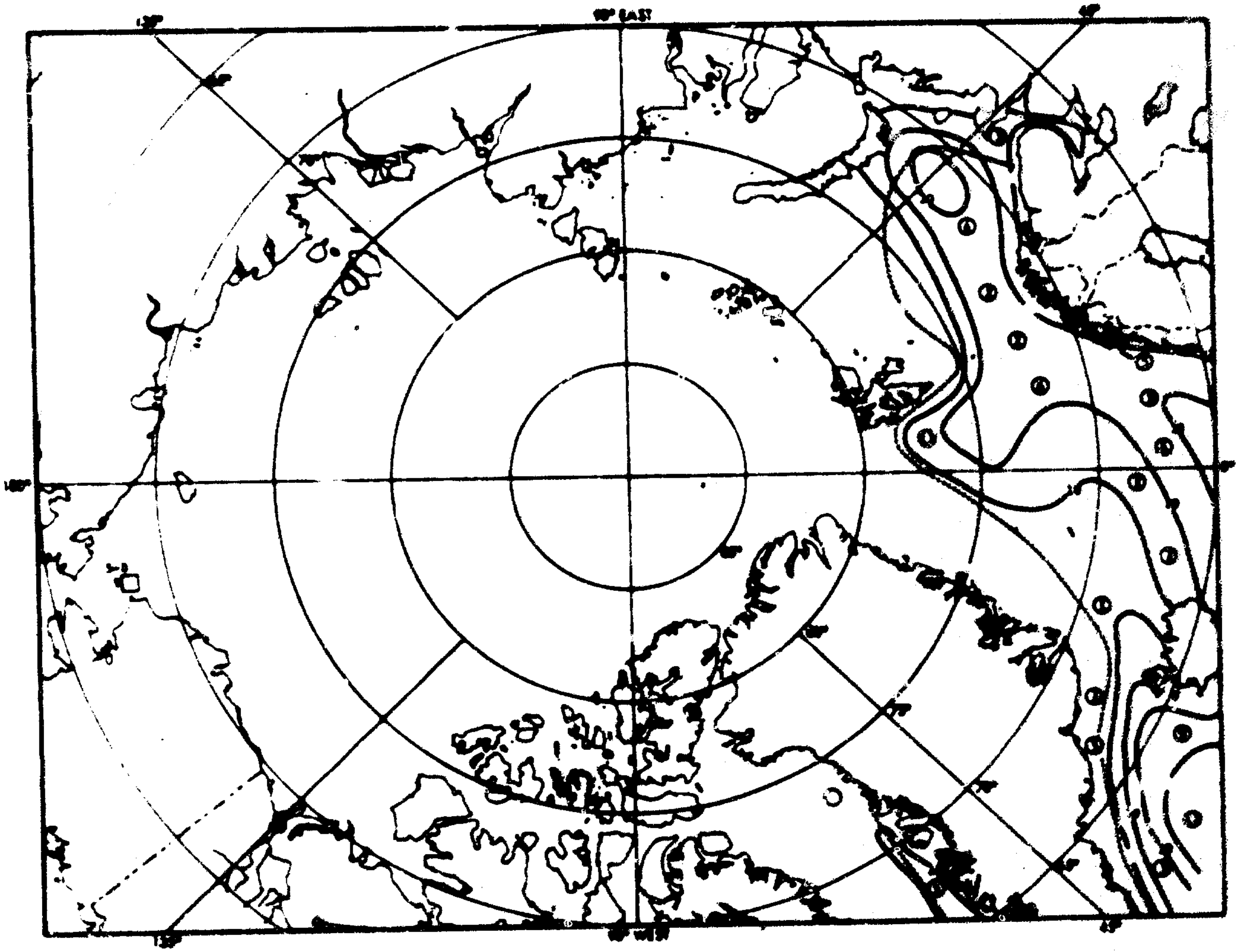
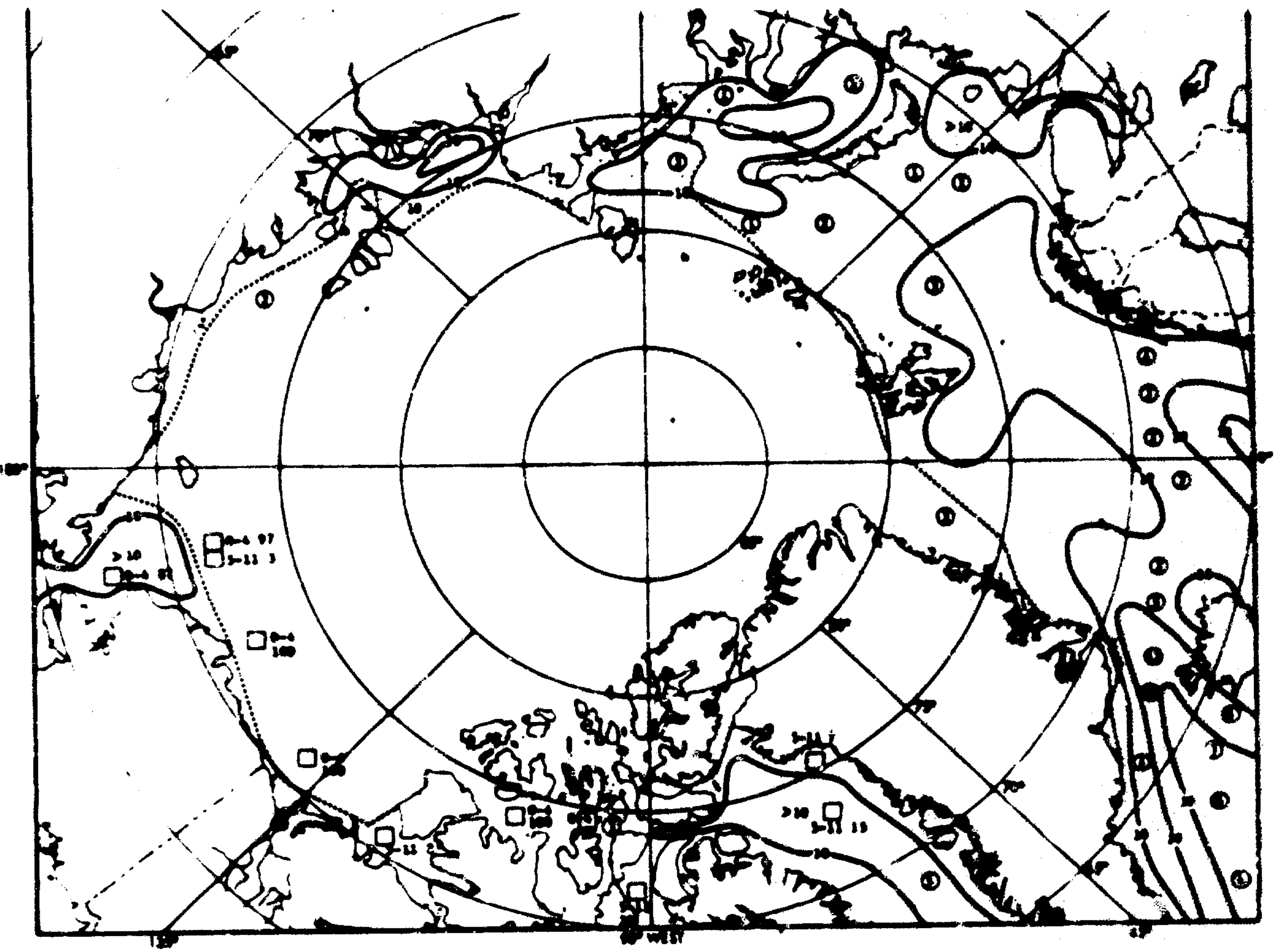


Figure 8-9: SEA STATE SPRING



ISOLINES SHOW PERCENT FREQUENCY OF SEAS 8 FEET AND GREATER.

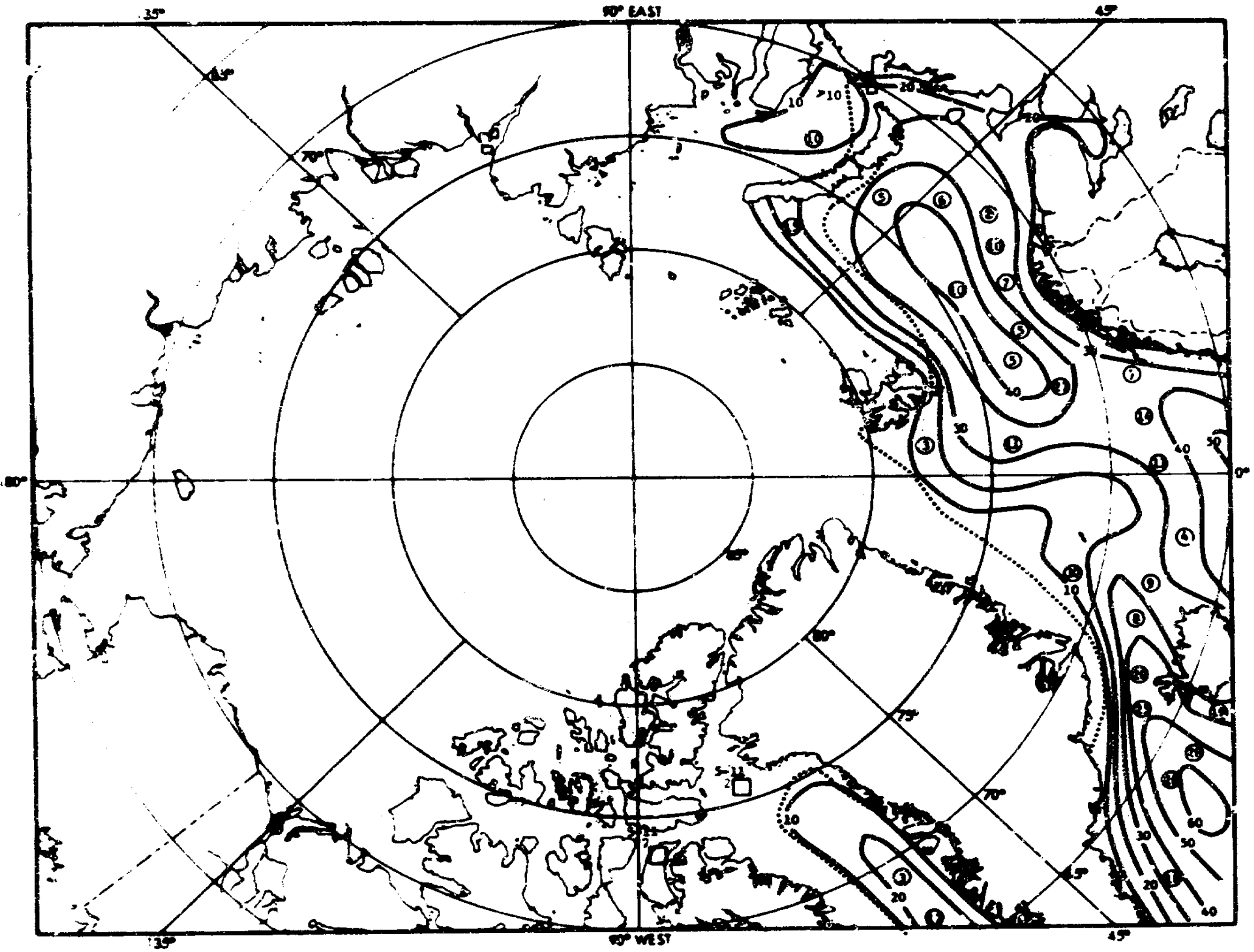
PERCENT FREQUENCY OF SEAS 12 FEET OR GREATER.

—— MEAN LIMIT OF ICE; 5/10 COVERAGE.

PERCENT FREQUENCY OF SEAS OF INDICATED HEIGHT E.G. 5 TO 8 FEET 2%

REF: HO-705 AND UNPUBLISHED DATA

Figure 8-10: SEA STATE SUMMER



LEGEND

ISOLINES SHOW PERCENT FREQUENCY OF SEAS 5 FEET AND GREATER.

PERCENT FREQUEN OF SEAS 12 FEET OR GRE.

—— MEAN LIMIT OF ICE 5/10 COVERAGE.

REF: HO-705

Figure 8-11: SEA STATE FALL

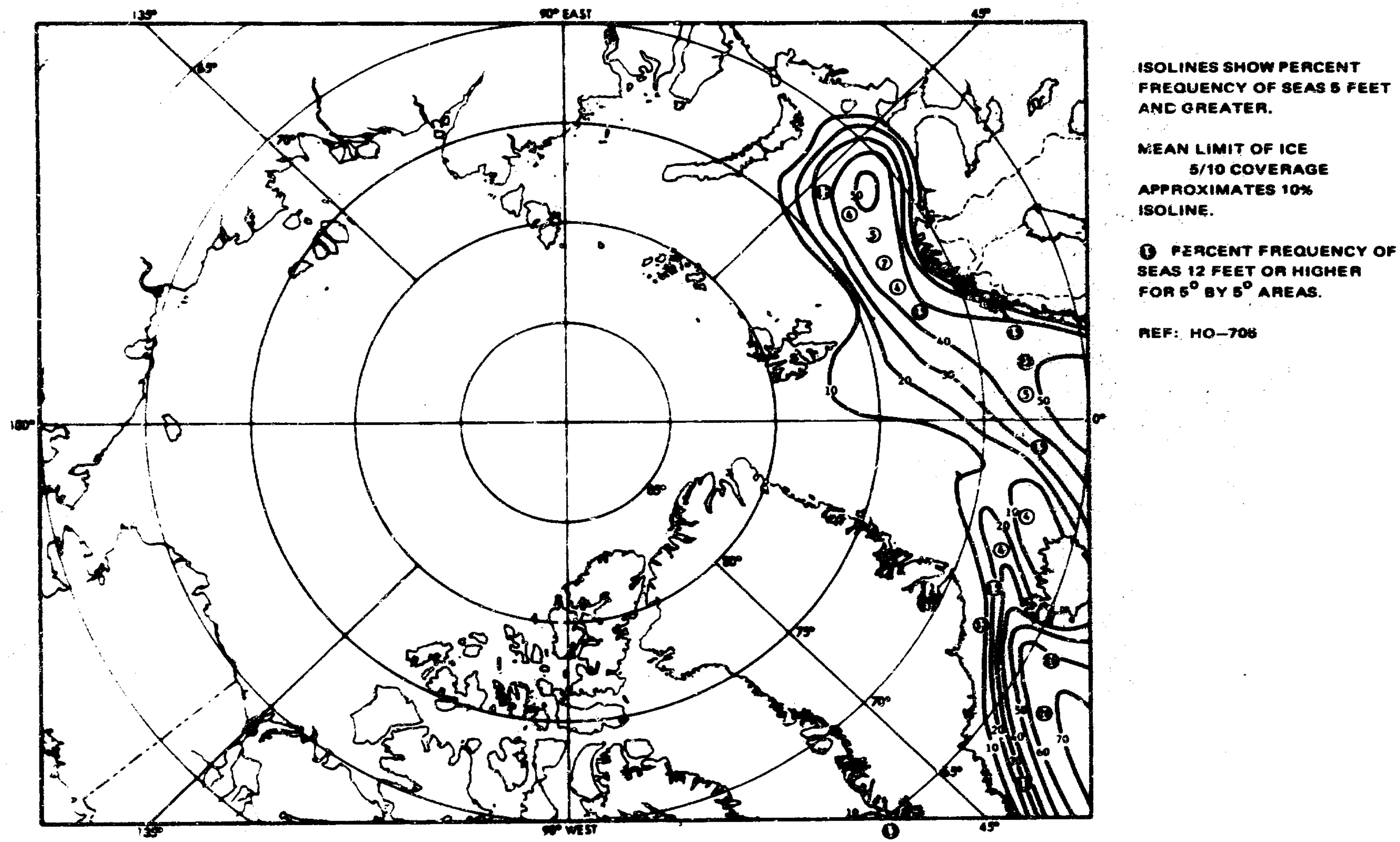


Figure 8-12: SEA STATE WINTER

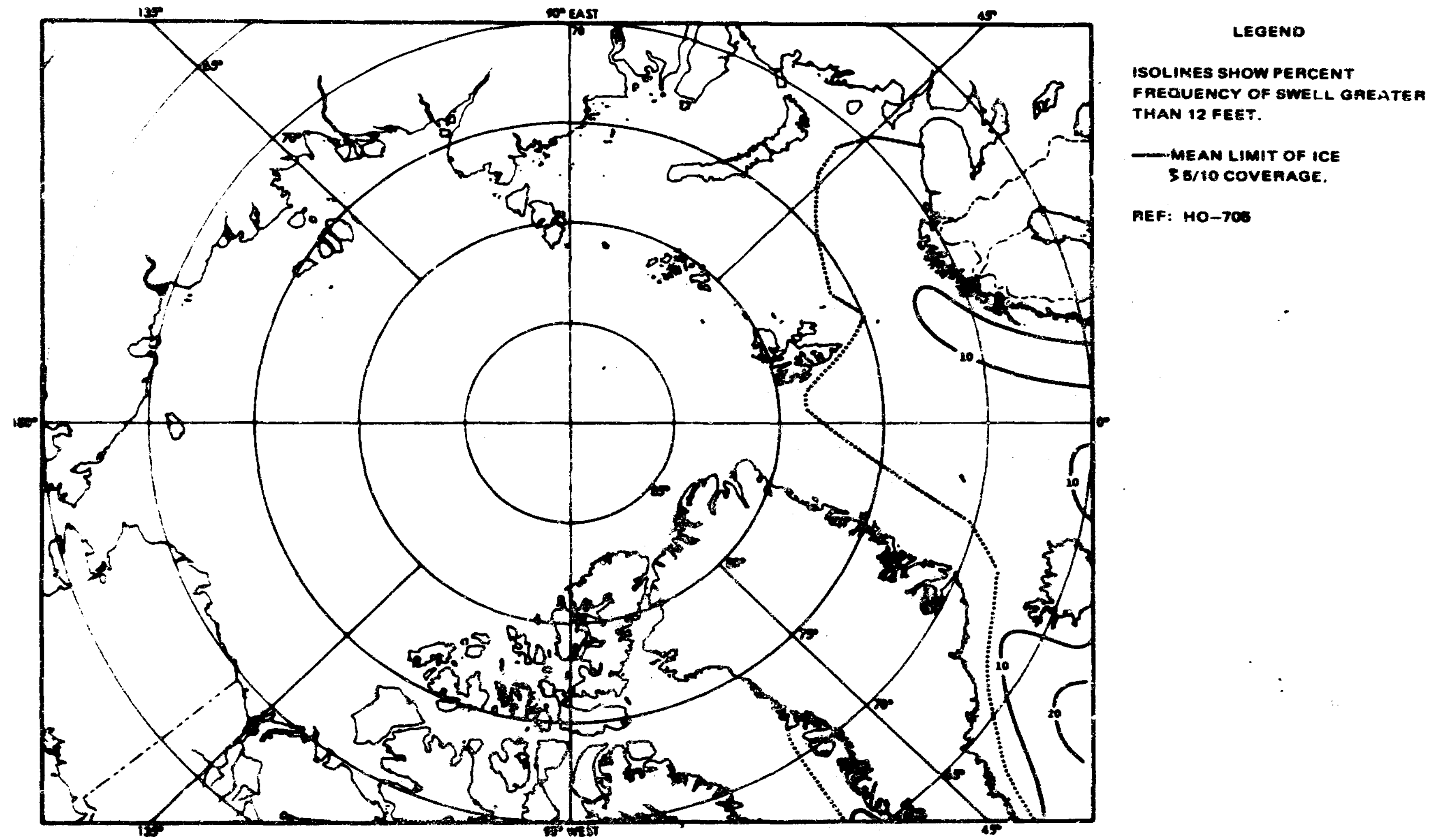


Figure 8-13: SWELL SPRING

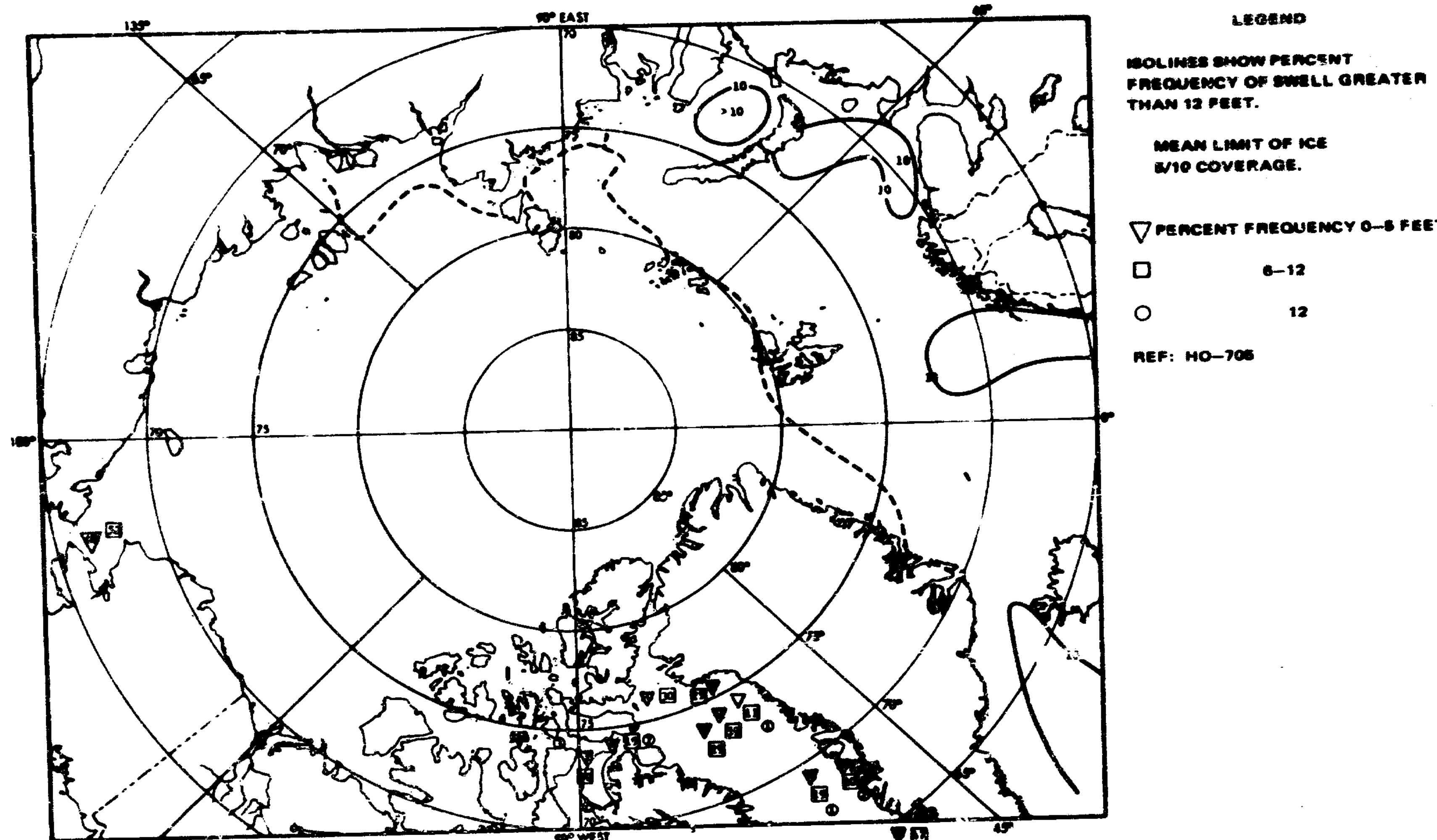
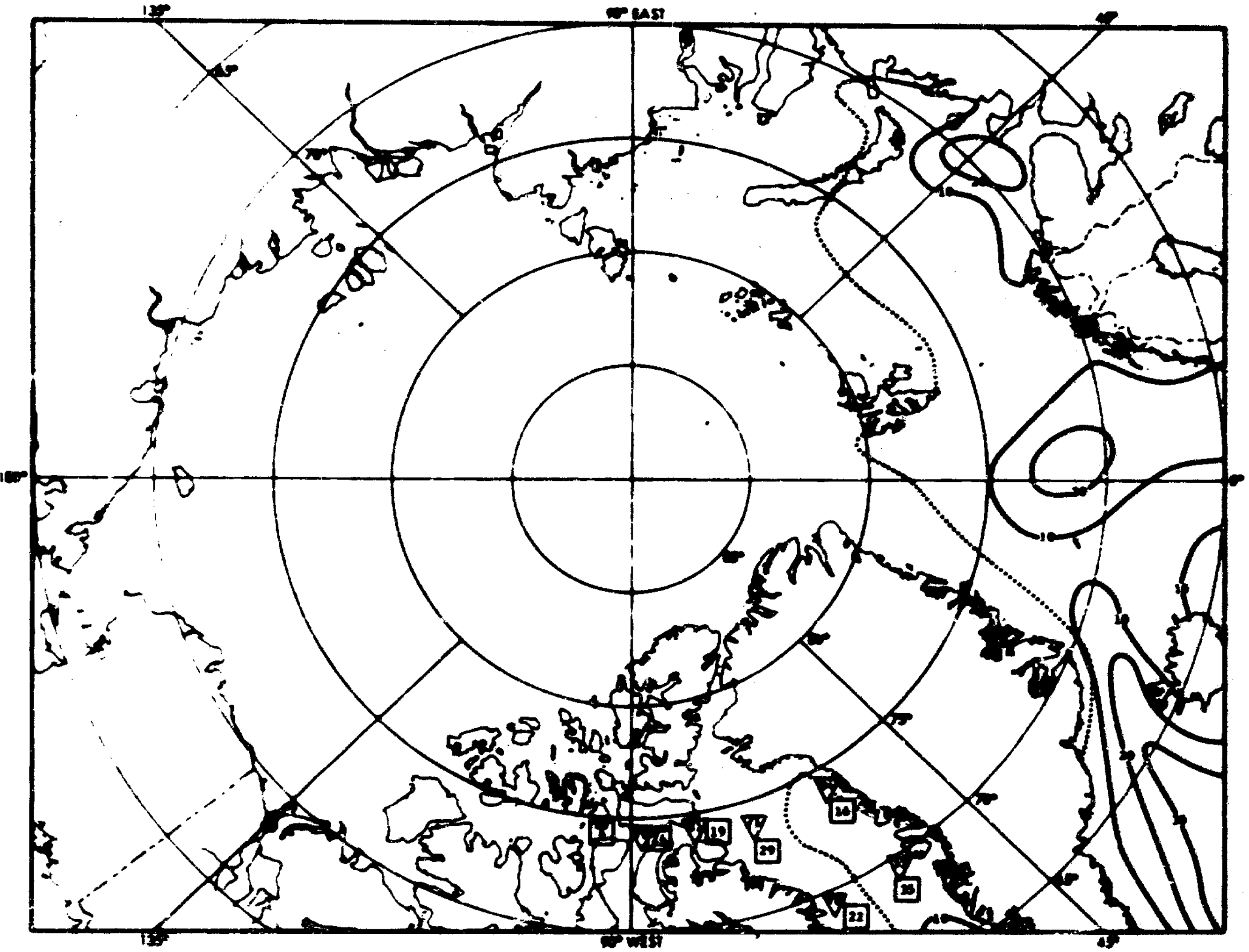


Figure 8-14: SWELL SUMMER



LEGEND

ISOLINES SHOW PERCENT FREQUENCY OF SWELL GREATER THAN 12 FEET.

— MEAN LIMIT OF ICE ≥ 5/10 COVERAGE.

NOTE: SWELL 8–10 FEET REPORTED BEAUFORT SEA 71° 21'N 138° 18'W OCTOBER 1960. 10/10 COVERAGE OF YOUNG ICE (6"–8")

▽ PERCENT FREQUENCY OF SWELL 0–8 FEET.

□ PERCENT FREQUENCY OF SWELL 8–12 FEET.

REF: HO–705

Figure 8-15: SWELL FALL

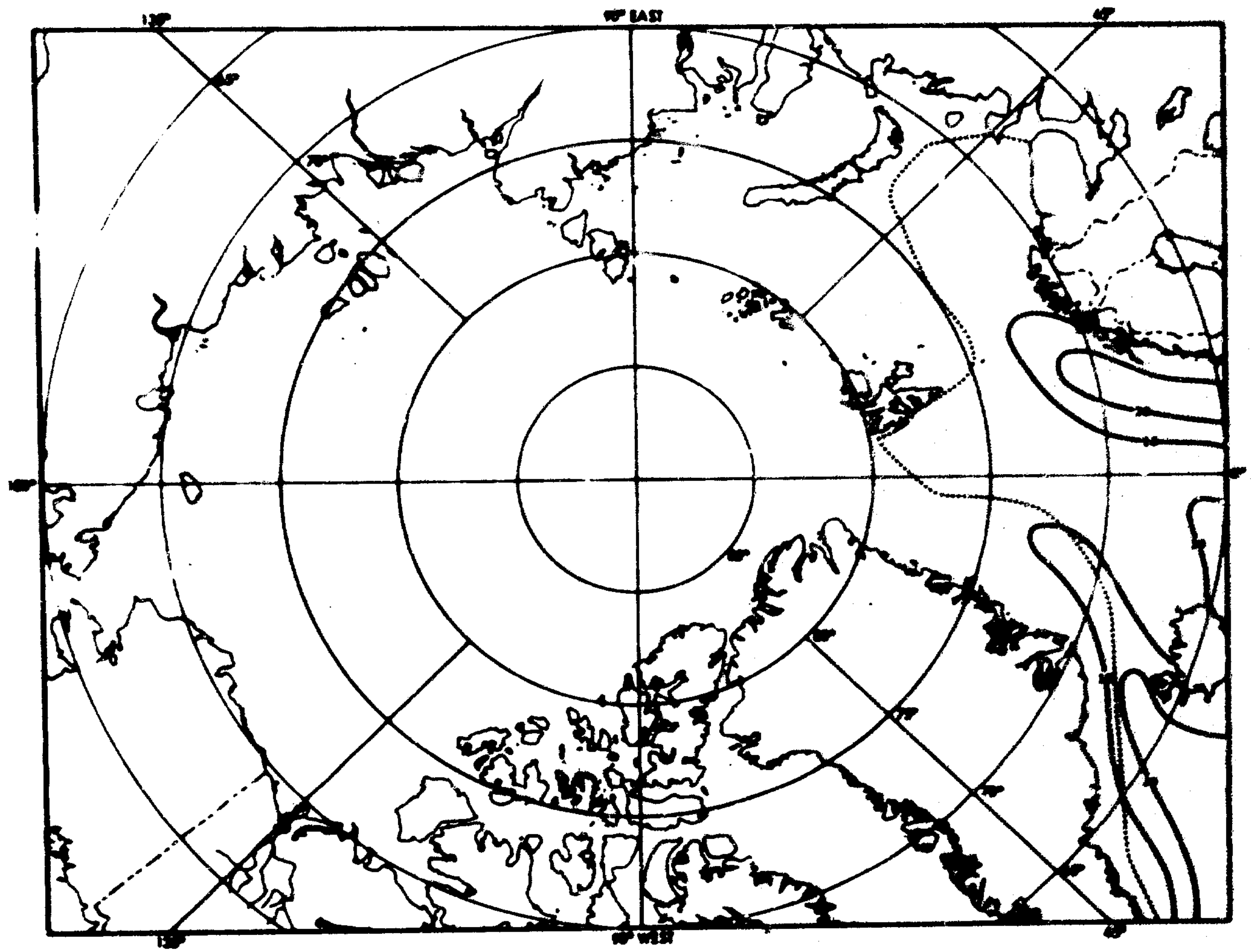


Figure 8-16: SWELL WINTER

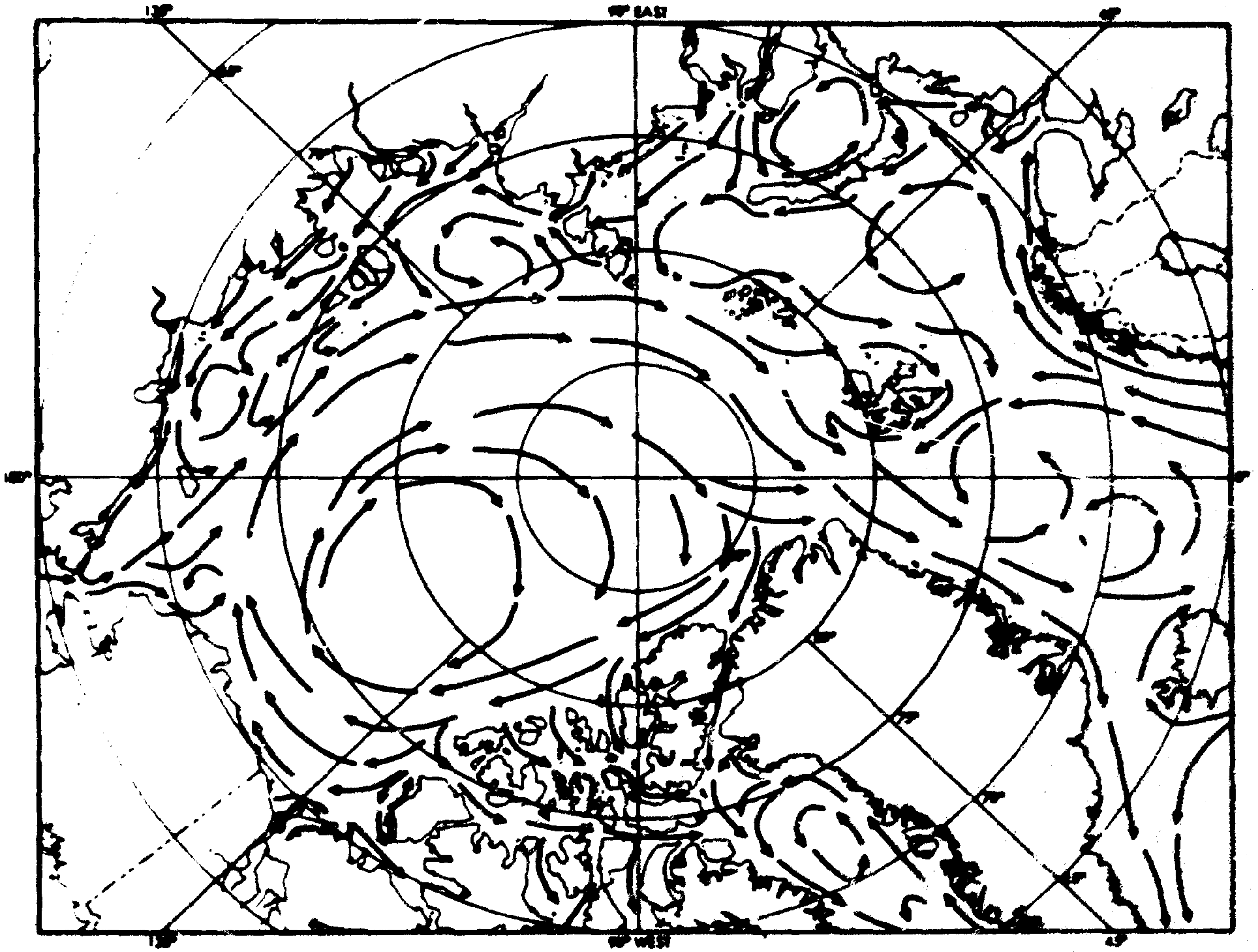


Figure 8-17: GENERALIZED ARCTIC SURFACE CIRCULATION

seas generally have counterclockwise gyres with easterly setting currents. The flow from the Bering Sea is usually northward through the Bering Strait, but occasionally a southerly flow occurs along the western edge of the strait (Reference 14).

The patterns of surface circulation are generally reliable in the areas that are ice free; however, in the major portion of the ice pack the circulation patterns have been derived from drift station data, which is undoubtedly influenced at least in part by atmospheric circulation as it affects movement of the ice.

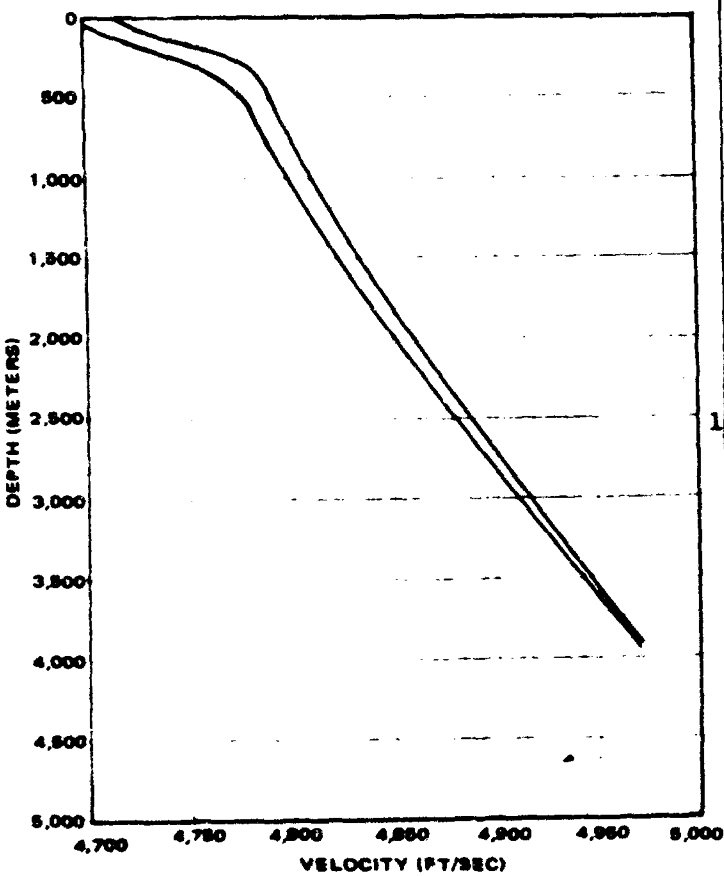
8.3.5 Sound Propagation

Throughout the central portion of the Arctic Basin, sound propagation conditions are essentially uniform. This uniformity results from the stability of both the temperature and salinity variations, both with time and over a wide geographic distribution. The temperature of the water remains within the range of +0.8 and -1.8°C. Most of the variations in both temperature and salinity occur within the upper 600 meters. Three water masses have been identified in the Arctic Ocean. The uppermost layer (Arctic Water) is a low-salinity surface layer that extends to about 200 meters. The seasonal variations of both temperature and salinity that result from the freezing and melting of the ice pack occur within this layer. Temperature is generally close to the freezing point. The second layer extending to about 600 meters originates in the Atlantic. The temperature of this water is above 0°C and is characterized by comparatively high salinities. From 600 meters to the bottom the water has a temperature below 0°C and is of constant salinity.

The three water masses essentially determine the characteristics of the sound velocity. The deep sound channel (SOFAR channel) exists in the form of a half channel with the bottom ice surface acting as the upper boundary. As a result long-range sound propagation is possible and is disturbed chiefly by the roughness of the under surface of the ice.

Observations of sound velocity in arctic waters are quite sparse. Data within the main basin has been obtained from drifting stations, with observations north of Greenland and north of Point Barrow. No data for the area north of the East Siberian Sea and Laptev Sea is available.

The available data indicates that the sound velocity profile in the main basin is quite uniform and shows little variation with season. All observations fall within the narrow envelope shown in Figure 8-18. Within the top few meters the velocity is near 4,700 ft/sec although some observations taken at the surface where salinity is low and the water is warmer during the summer indicate that the velocity may drop to near 4,600 ft/sec. The velocity



OBSERVATIONS IN POLAR BASIN APRIL—SEPTEMBER (41)
ALL POINTS OF ALL PROFILES FALL WITHIN ENVELOPE.

SOURCE: U.S. OCEANOGRAPHIC OFFICE—UNFULISHED DATA

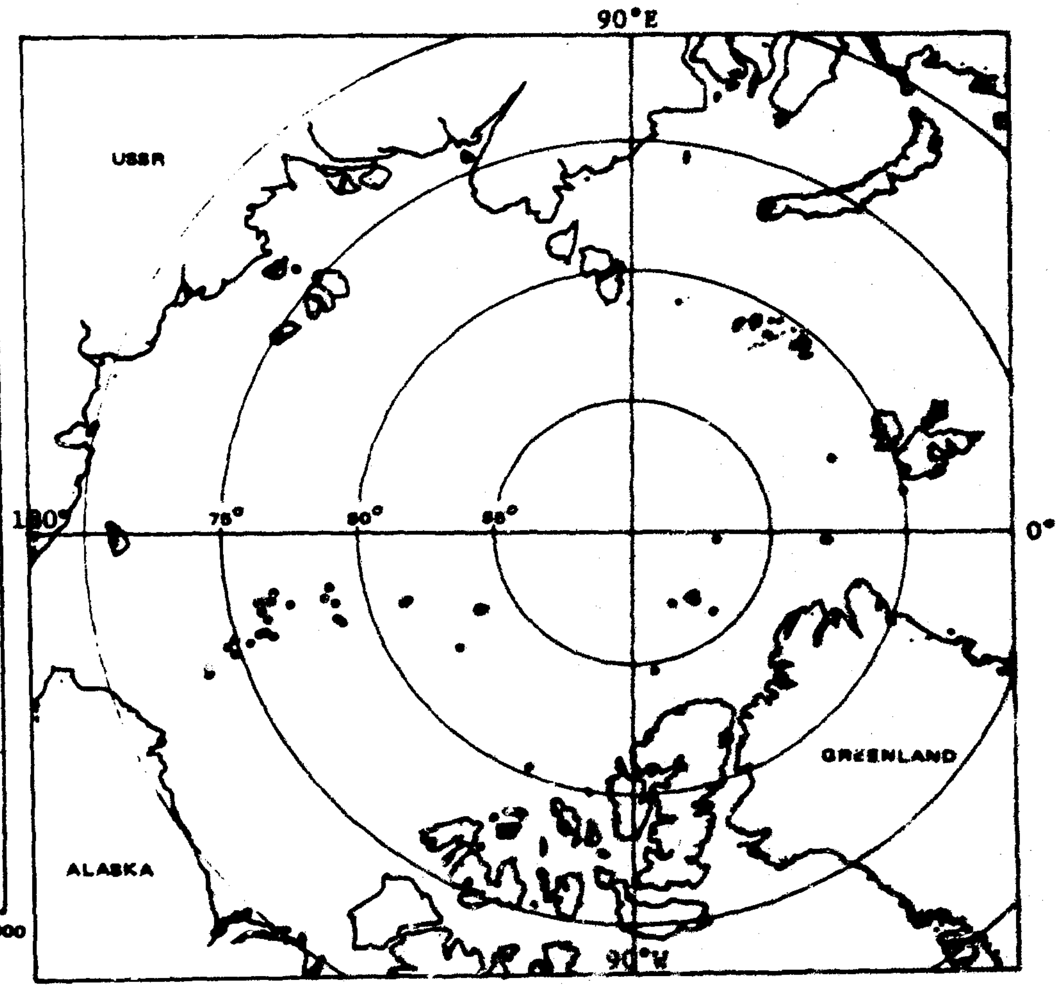


Figure 8-18: SOUND VELOCITY PROFILE MAIN ARCTIC BASIN

increases rather uniformly between about 30 to 50 meters to 4,780 ft/sec. The profile shows a rather sharp break at that depth, increasing quite uniformly with depth to a velocity of 4,975 ft/sec at 4,000 meters. Variation between observations decreases with increase in depth.

The greatest variation in observations for which data is available occurs in the Barents, Norwegian, Greenland Seas area as seen by the envelopes shown in Figure 8-19.

Observations have been made in the southern Chukchi during summer (Figure 8-20) and autumn (Figure 8-21). Except for one observation close to the Siberian coast (No. 58, Figure 8-20), all velocities observed fell between 4,700 and 4,800 ft/sec. In the one exception noted, a velocity of 4,640 ft/sec was observed in the upper 5 meters. In this area, where the influence of the Bering Strait flow is significant, the velocity profiles varies appreciably with station location.

The sound propagation reaches long ranges by repeatedly reflecting from the bottom surface of the ice following refraction in the deeper water. This combination of conditions creates unique propagation conditions in the arctic. Both high and low frequencies are rapidly attenuated as a result of reflection losses at high frequency and ineffective trapping in the channel at low frequencies. Best propagation has been found to be in the 15 to 30-Hz range. In addition the typical time-stretching characteristic that has been noted in SOFAR pulses is present, resulting in significant pulse lengthening.

Transmission loss has been measured chiefly with signals from explosive sources. The results from various tests are somewhat inconsistent; however, they can serve to establish some general information about the loss to be expected. Figure 8-22, after Milne, shows the transmission loss at 100 Hz as a function of range and serves to illustrate the effect of bottom ice roughness. The loss increases rapidly with frequency. (Reference 22 and 23)

Ambient noise characteristics under an ice cover are considerably different than those found in the open ocean. In discontinuous floe-ice, noise levels 5 to 10 db higher than in open water have been measured. Shore-fast ice under rising temperatures creates conditions such that abnormally low noise levels occur. The amplitude and character of the ambient noise is highly variable and depends on specific ice, wind, snow, and temperature conditions. Under conditions of decreasing air temperatures, cracks begin to form in the ice that result in impulsive noise. This reverts to Gaussian on a rising temperature. Windblown snow striking the ice and wind effects over open water in the pack increase noise levels. The bumping of ice flows represent still another source of noise. The variations of conditions are such that it is not possible to predict either the noise spectra or amplitude at this time.

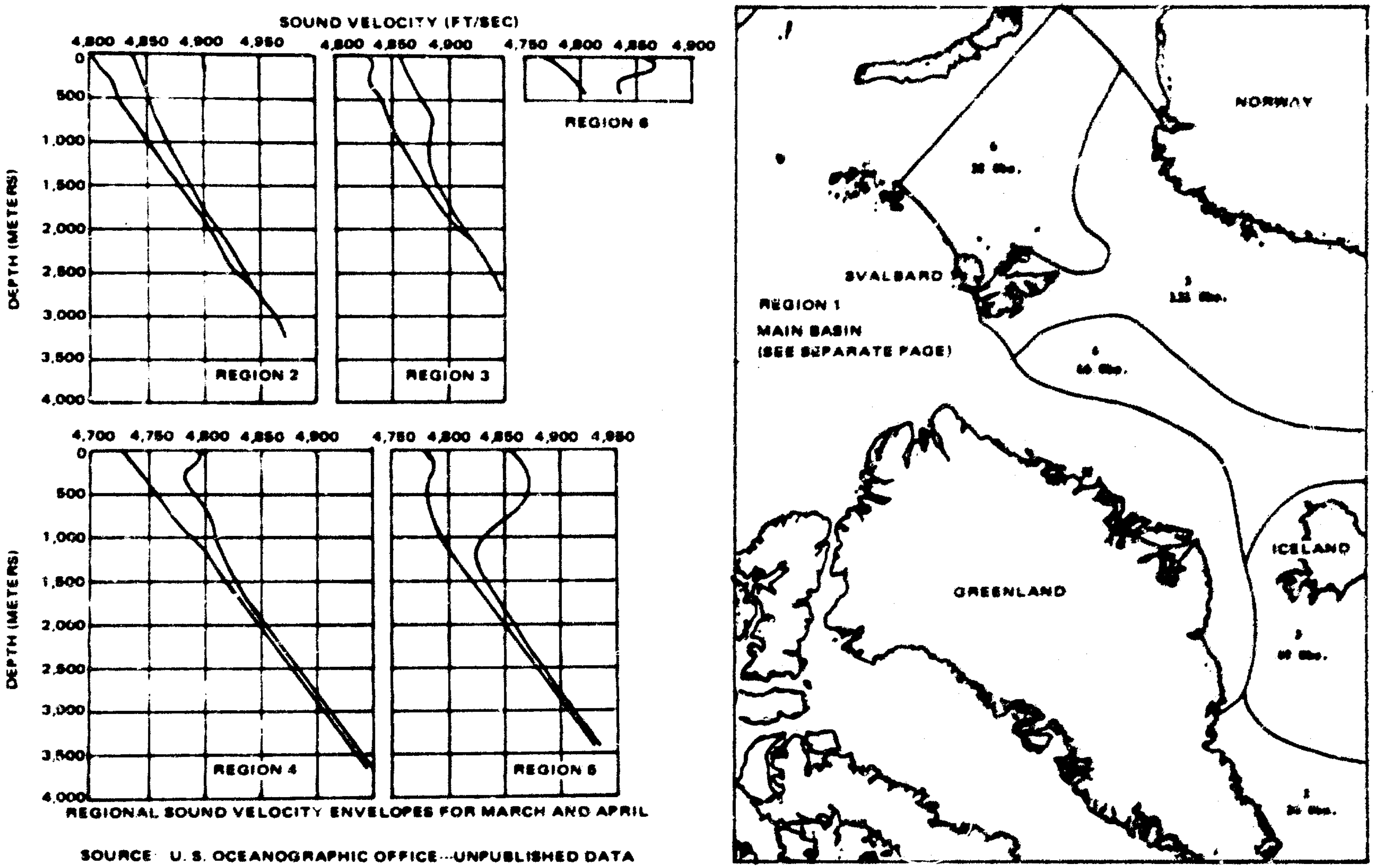
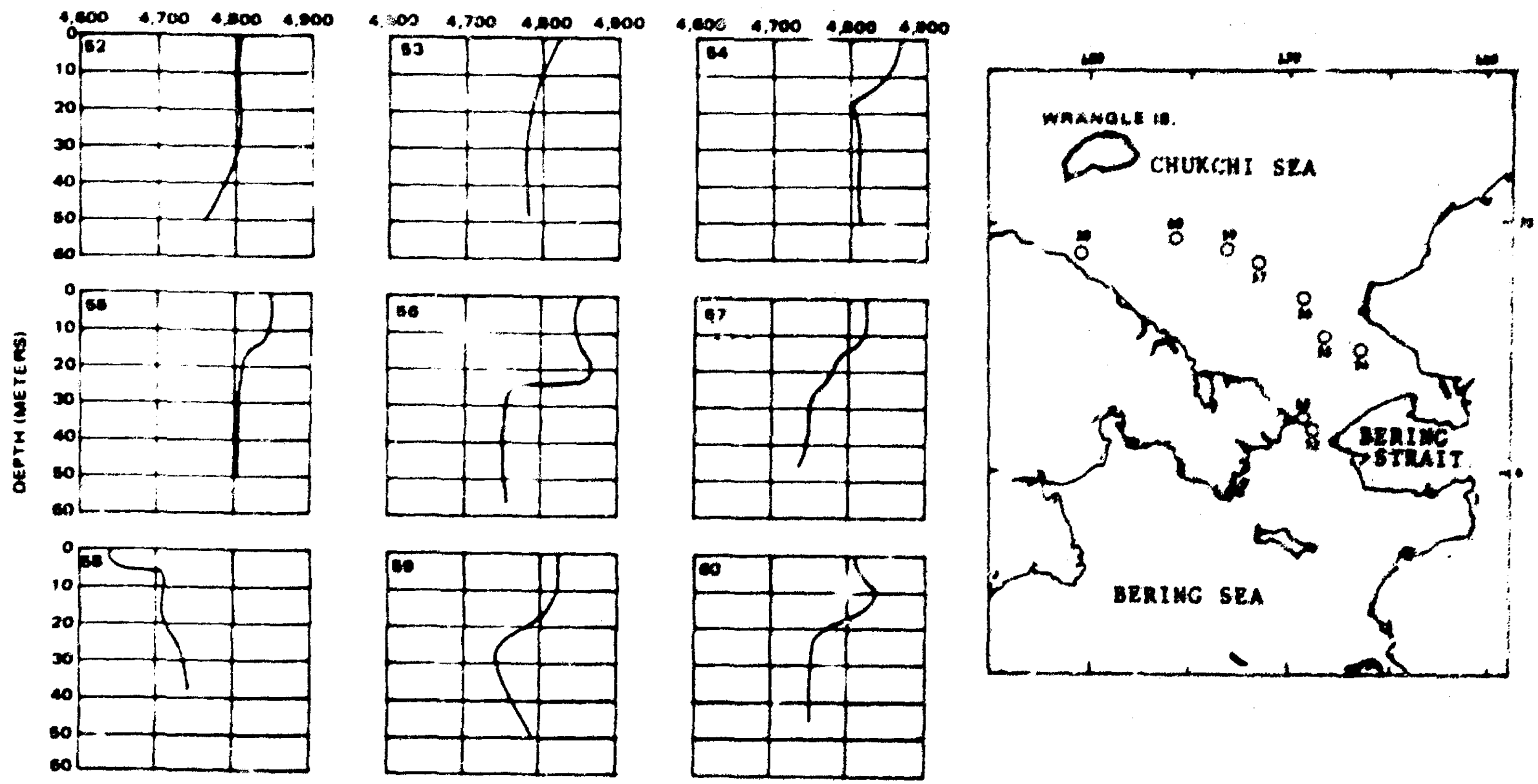
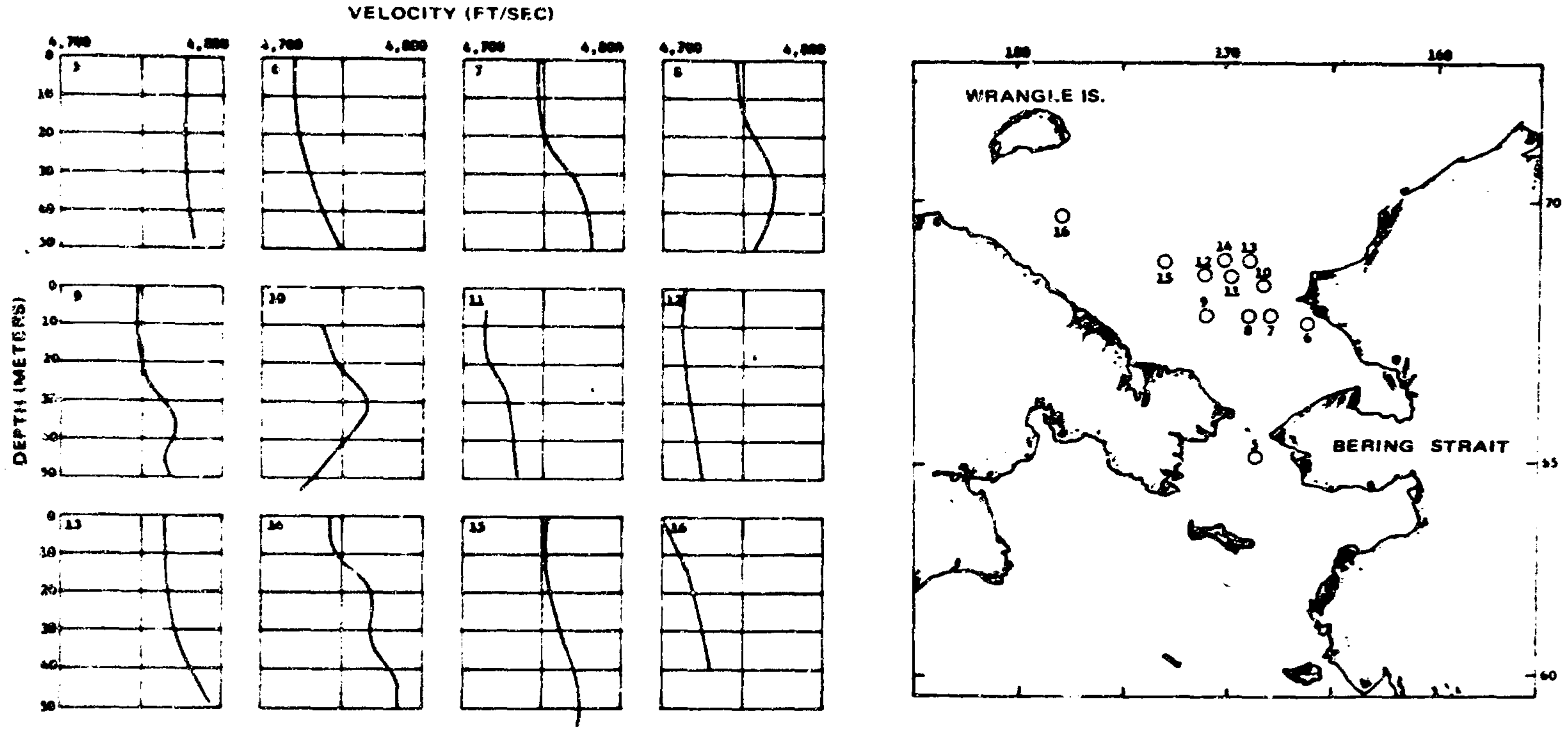


Figure 8-19: REGIONAL SOUND VELOCITY ENVELOPES FOR MARCH AND APRIL



SOURCE: U. S. OCEANOGRAPHIC OFFICE - UNPUBLISHED DA

Figure 8-20: VELOCITY---CHUKCHI SEA AUTUMN



SOURCE: U.S. OCEANOGRAPHIC OFFICE--UNPUBLISHED DATA

Figure 8-21: UNDERWATER SOUND VELOCITY---CHUKCHI SEA AUTUMN

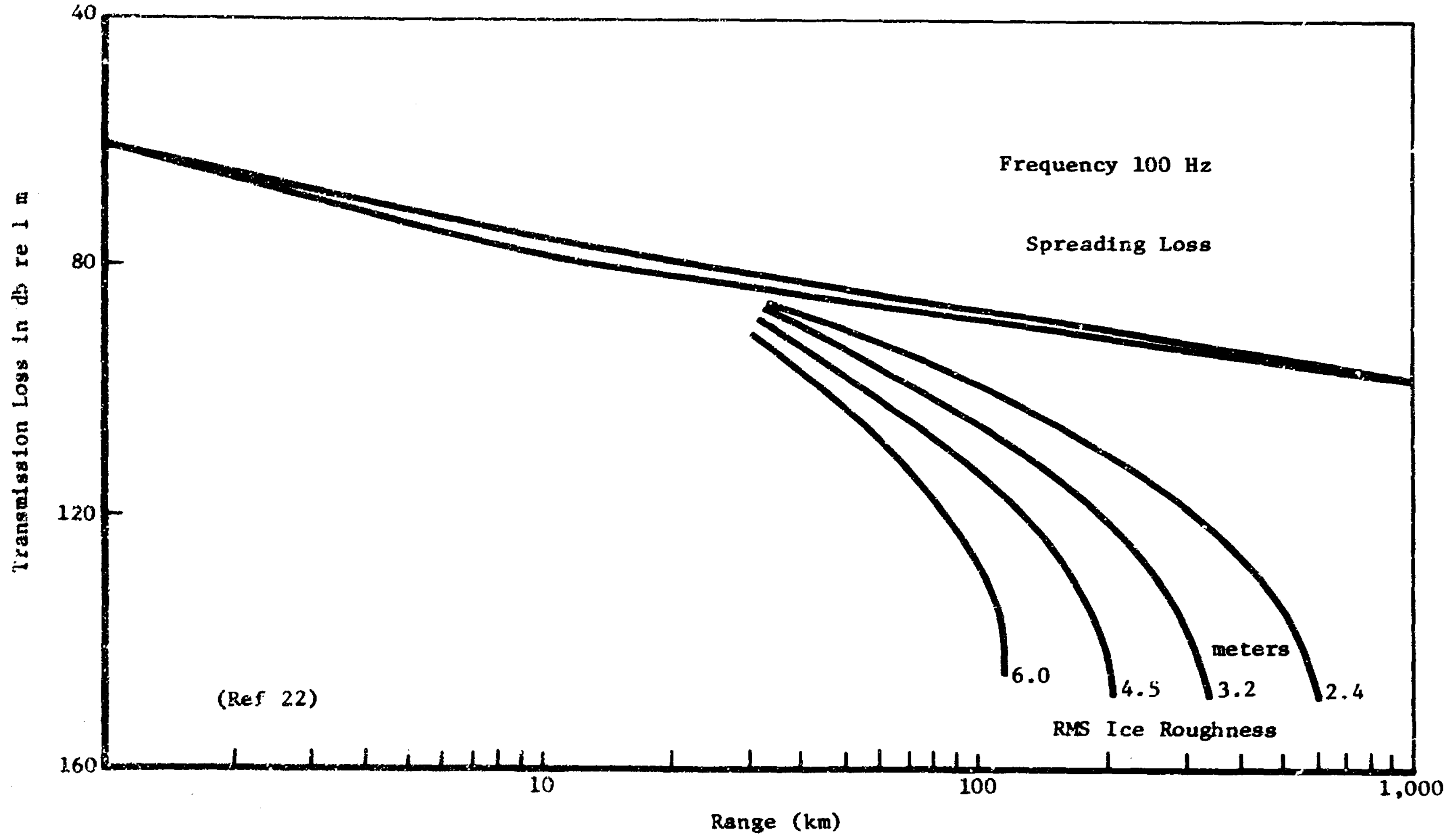


Figure 8-22: TRANSMISSION LOSS IN DB/METER AT 100 Hz

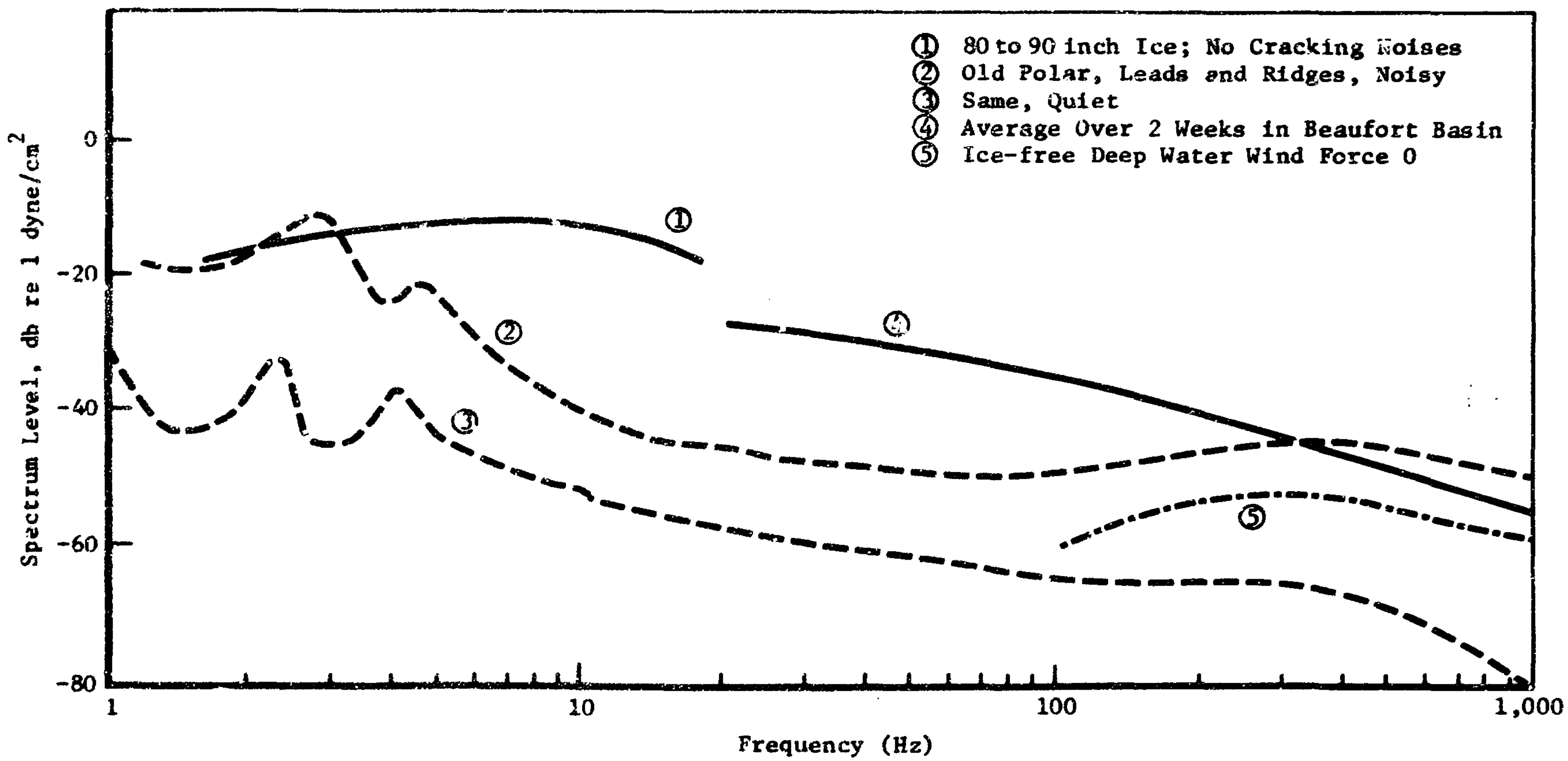


Figure 8-23: SPECTRA OF AMBIENT NOISE OBSERVED UNDER ICE (Ref 23)

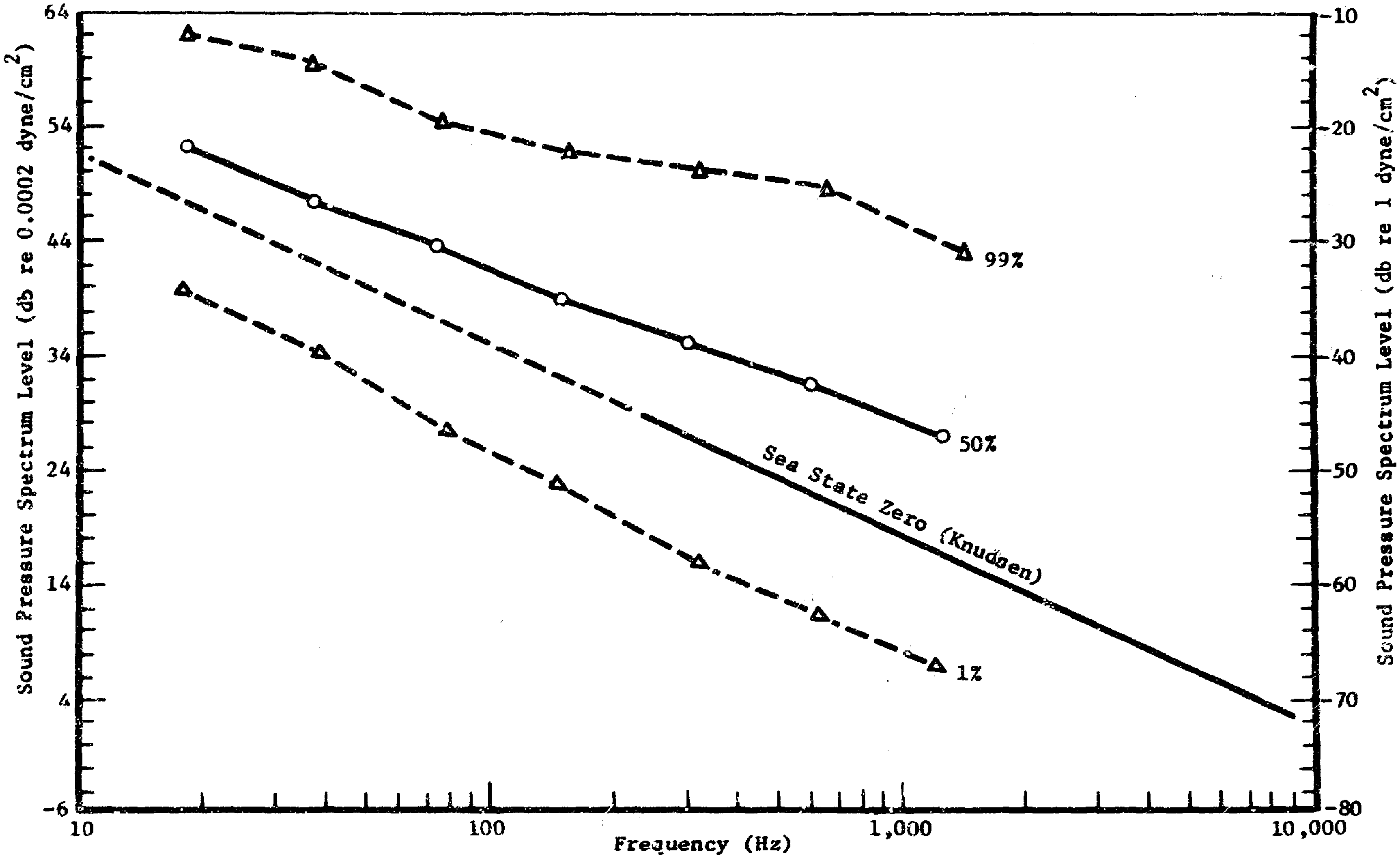


Figure 8-24: MEDIAN, 99, AND 1 PERCENTILES OF SOUND-PRESSURE LEVEL OF AMBIENT NOISE OBSERVED ON T-3 IN THE BEAUFORT SEA FOR PERIOD APRIL 1965 THROUGH FEBRUARY 1966 (Ref 24)

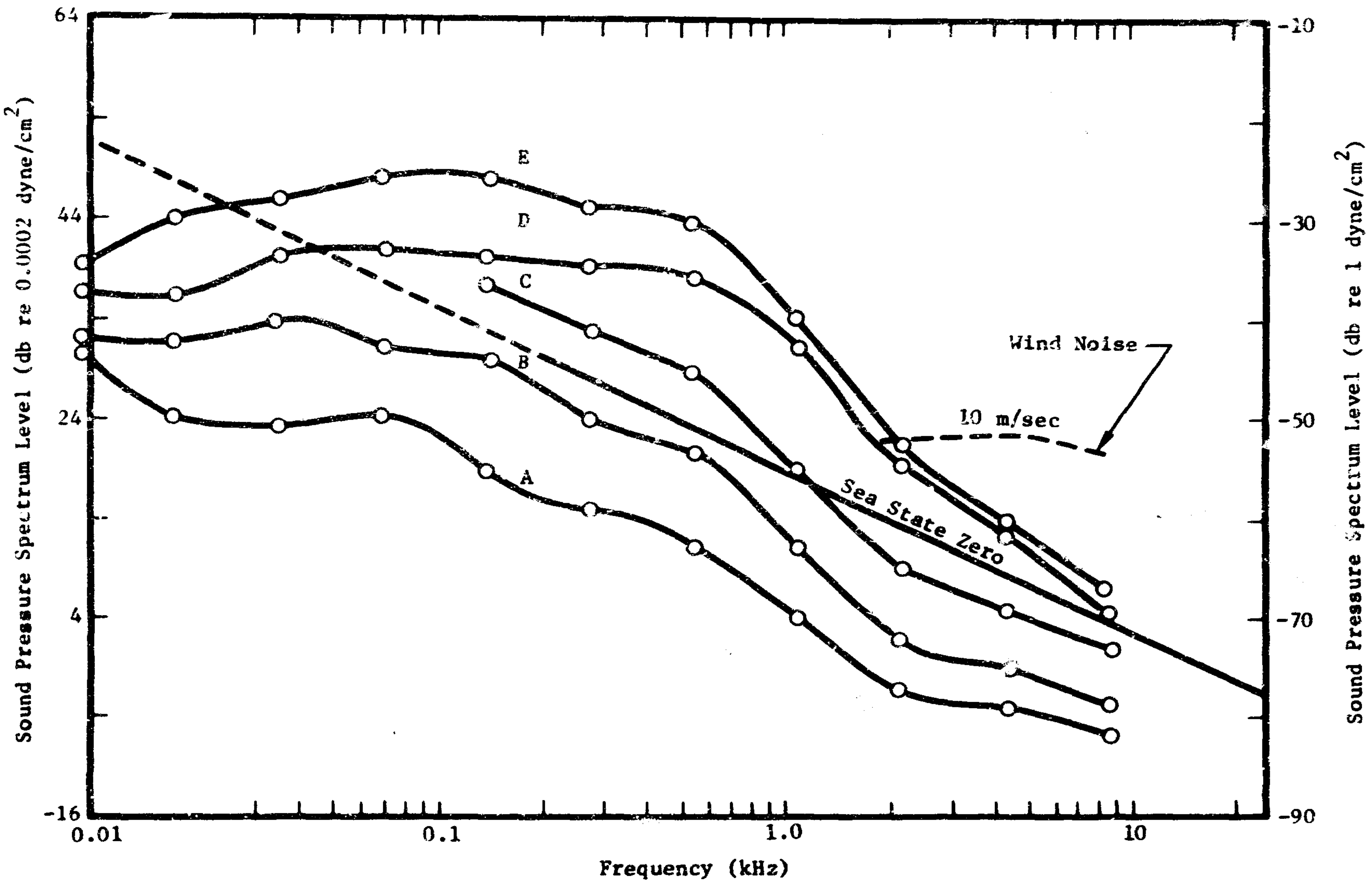


Figure 8-25: PRESSURE SPECTRA OF ICE CRACKING NOISE DURING AIR-COOLING PERIODS WITH ZERO WIND SPEED---TAKEN NEAR ELLEF RINGNES ISLAND (Ref 24)

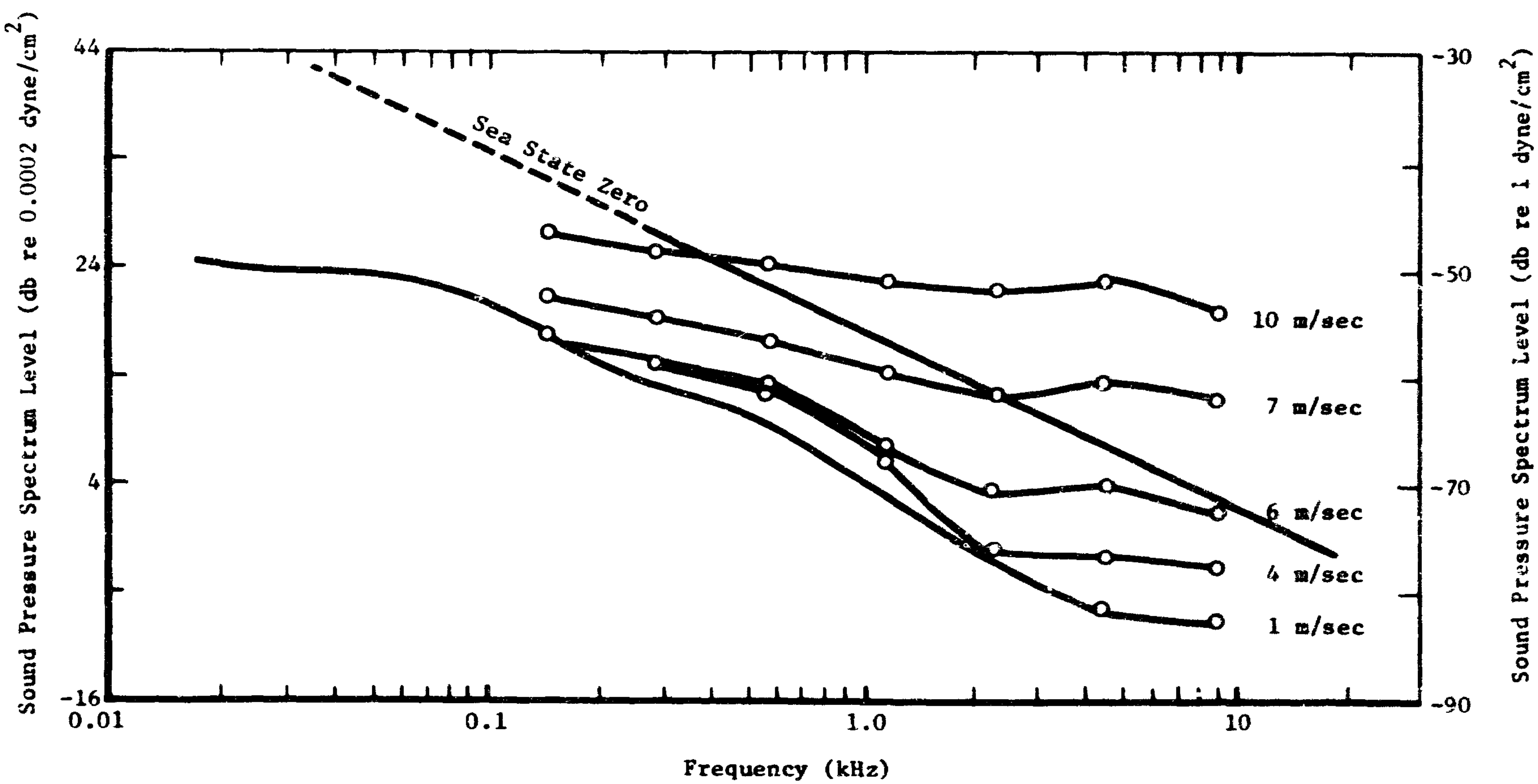


Figure 8-26: PRESSURE SPECTRA OF UNDER-ICE NOISE FOR DIFFERENT WIND SPEEDS WHEN RECORDED DURING AIR-WARMING TRENDS---TAKEN NEAR ELLEF RINGNES ISLAND (Ref 24)

At the lowest levels amplitudes are below the lowest Knudsen value for Sea State 0. At the highest measurements, up to 40 db higher have been observed under cracking ice and falling temperatures. Typical curves are shown in Figures 8-23 to 8-26. (References 23 and 24)

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9.0 MISCELLANEOUS DATA

9.1 ALBEDO

The albedo of both ice and water surfaces in the arctic has been measured to a limited extent. Most early measurements were restricted to ground station; however, airborne measurements have now been made in the U. S. S. R.

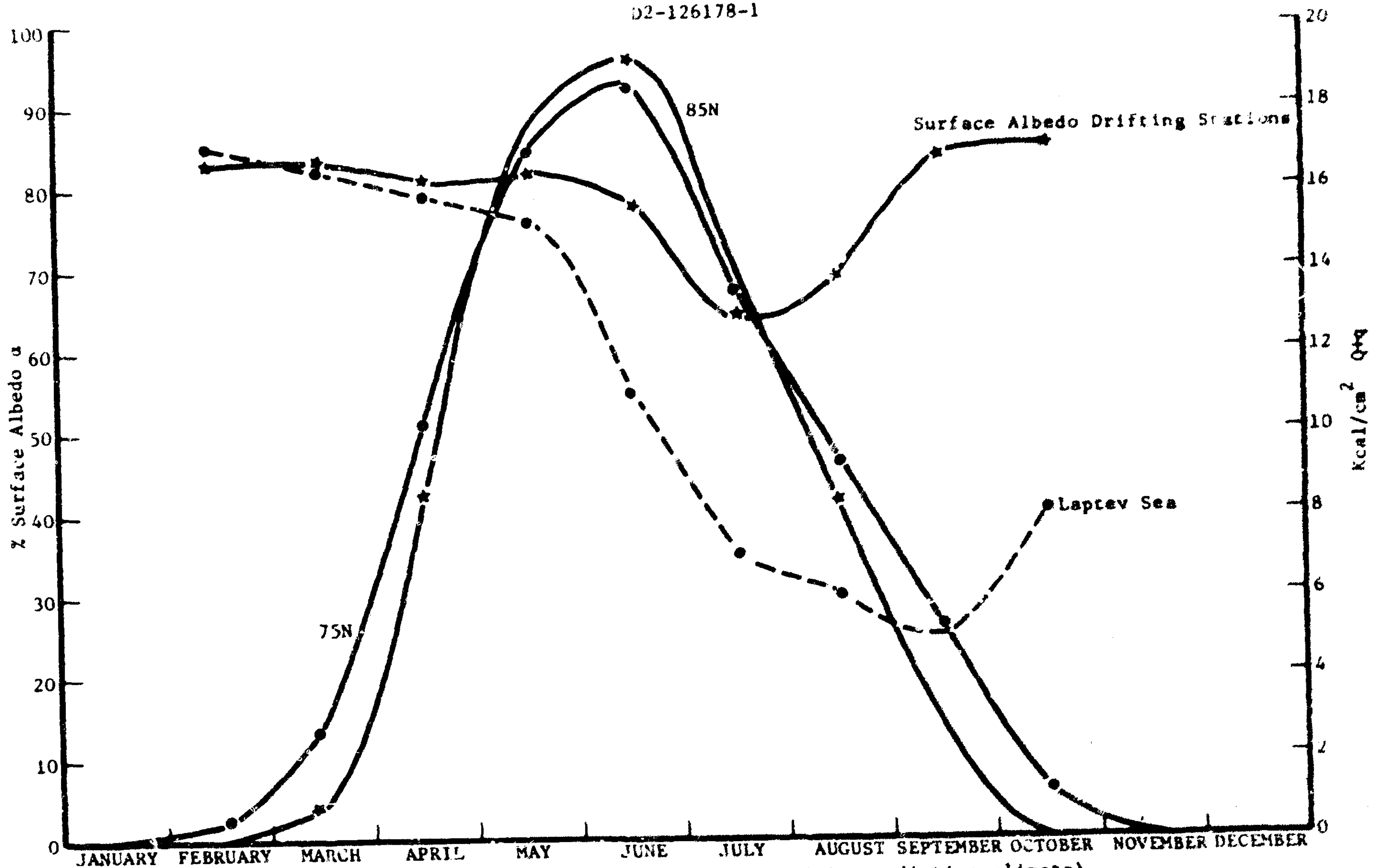
The albedo of both snow and ice depends as might be expected on the type and character of the surface. Freshly fallen snow behaves almost as an ideal frosted scattering surface with the albedo measuring between 85 and 90%. As the character and formation of the snow surface changes these values decrease, but at the same time very wide variations are evident. Melting snow may have an albedo as low as 30%, while fresh snow with a frozen crust has given values between 75 and 98%. Variations also occur during a typical day as a result of the changes that occur in the surface, meterological conditions, and sun angle. Table 9-1, after Koptev, show the range of values for various ice and snow conditions on the ice pack (Reference 1).

Figure 9-1 shows the seasonal variation of the surface albedo at 75° and 85° N as well as at some of the Soviet drifting stations and the Laptev Sea (Reference 2).

9.2 SUNLIGHT AND MOONLIGHT DURATIONS

In the higher latitudes, and particularly on the ice pack, the position of the sun and moon with respect to the horizon becomes an important factor since the periods of daylight, twilight, and moonlight reach extremes in duration. This has an important effect on all aspects of the environment, but in addition it is of importance in the context of practical operations. Visual and optical techniques are obviously degraded during the long periods of darkness; hence, problems of detection and identification are affected as is the problem of vehicle operation, unless supplementary systems are provided.

A sample set of curves of the semiduration of sunlight and moonlight as well as the duration of twilight are given in Figures 9-2 to 9-7. The semiduration curves show the number of hours between sunrise and the meridian transit and between meridian transit and sunset. The intersection between the date and the proper latitude line gives the semiduration. These curves are published annually in Air Almanac (Reference 3).



After Marshunova (from the heat budget of the Arctic basin and its radiation climate)

J. O. Fletcher Rand R444PR October 1965

Figure 9-1: SEASONAL SURFACE ALBEDO

Figure 9-2A:
SEMIDURATION OF SUNLIGHT

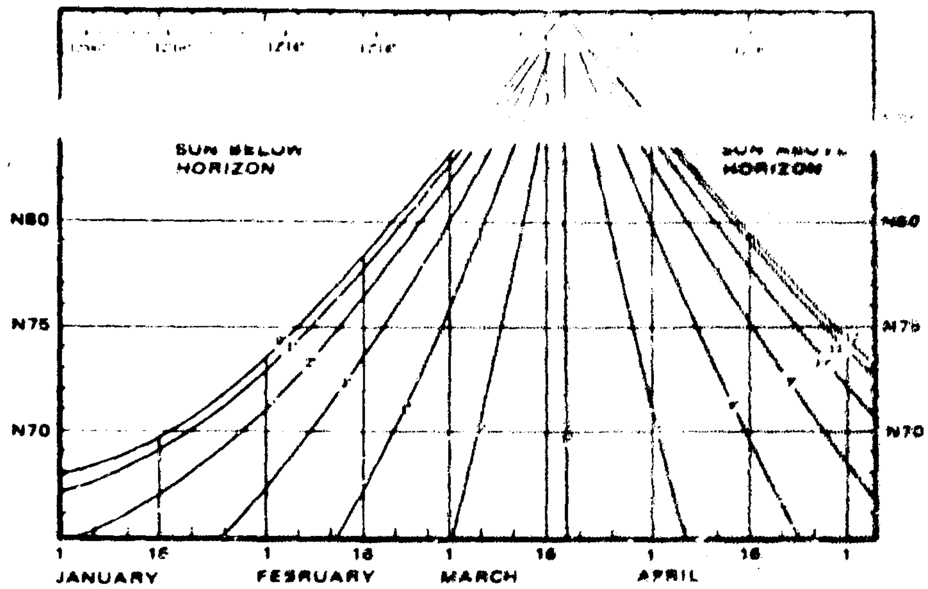


Figure 9-2B:
DURATION OF TWILIGHT

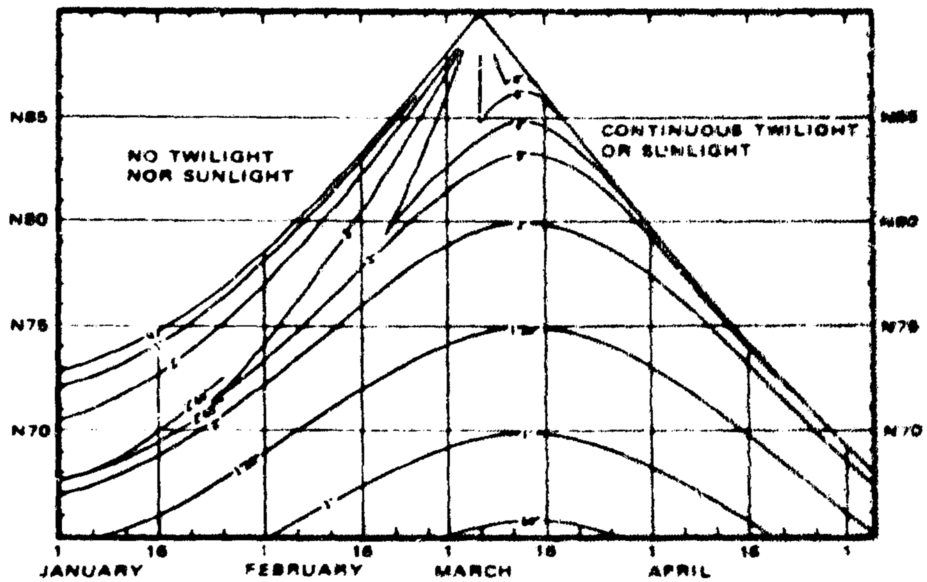


Figure 9-3A:
SEMIDURATION OF SUNLIGHT

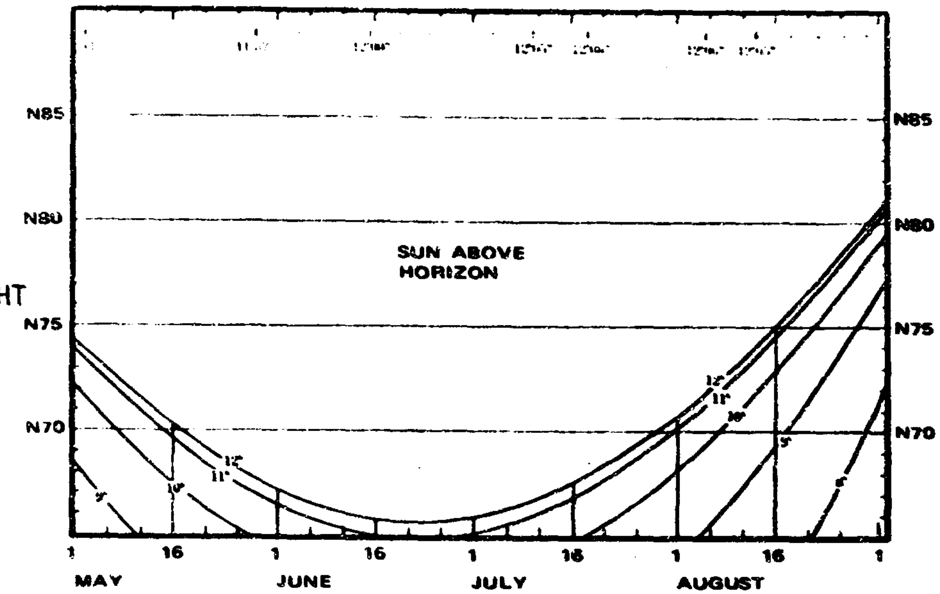


Figure 9-3B:
DURATION OF TWILIGHT

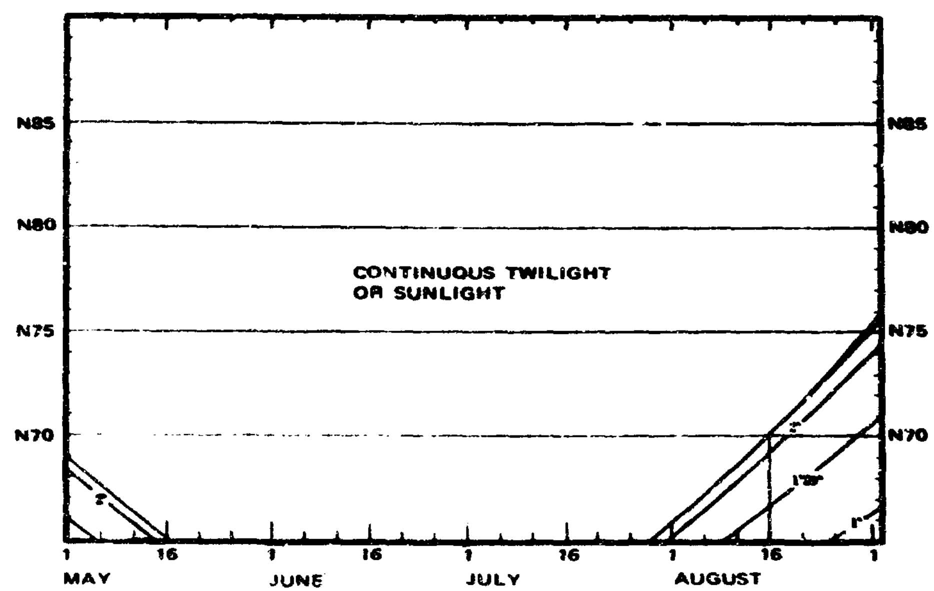


Figure 9-4A:
SEMIDURATION OF SUNLIGHT

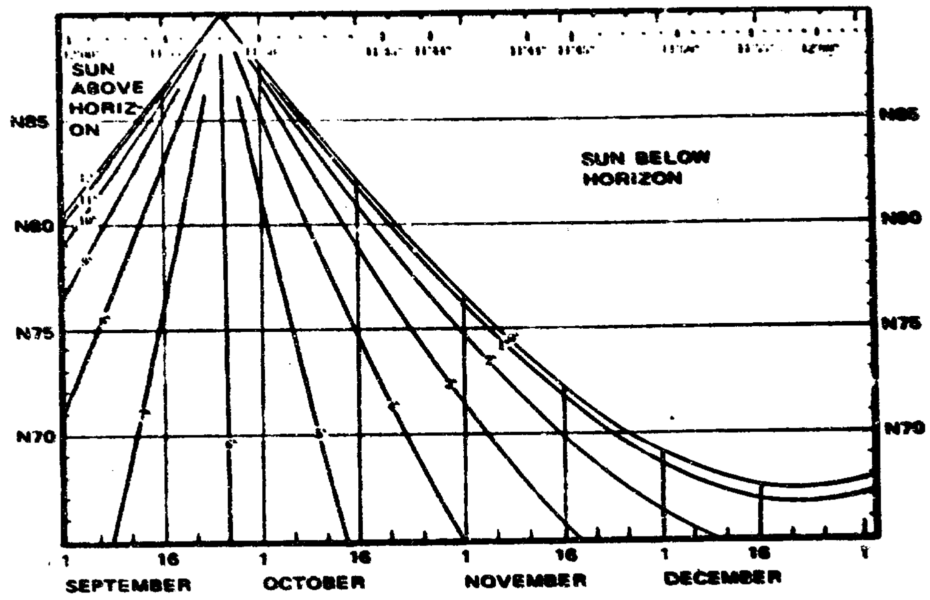
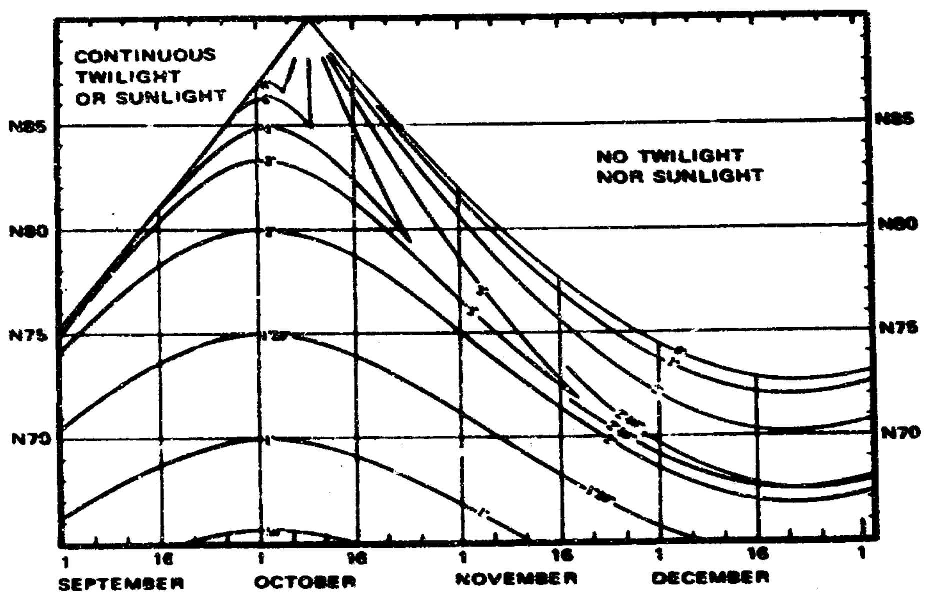


Figure 9-4B:
DURATION OF TWILIGHT



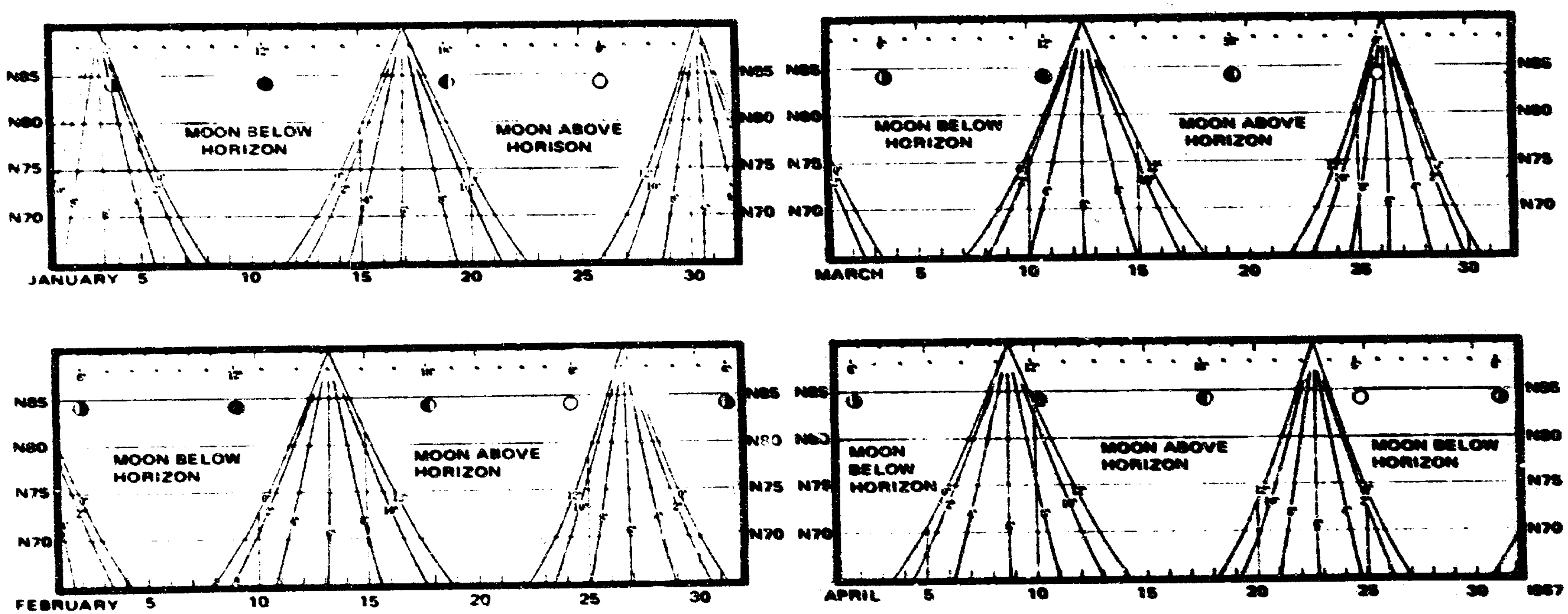


Figure 9-5: SEMIDURATION OF MOONLIGHT

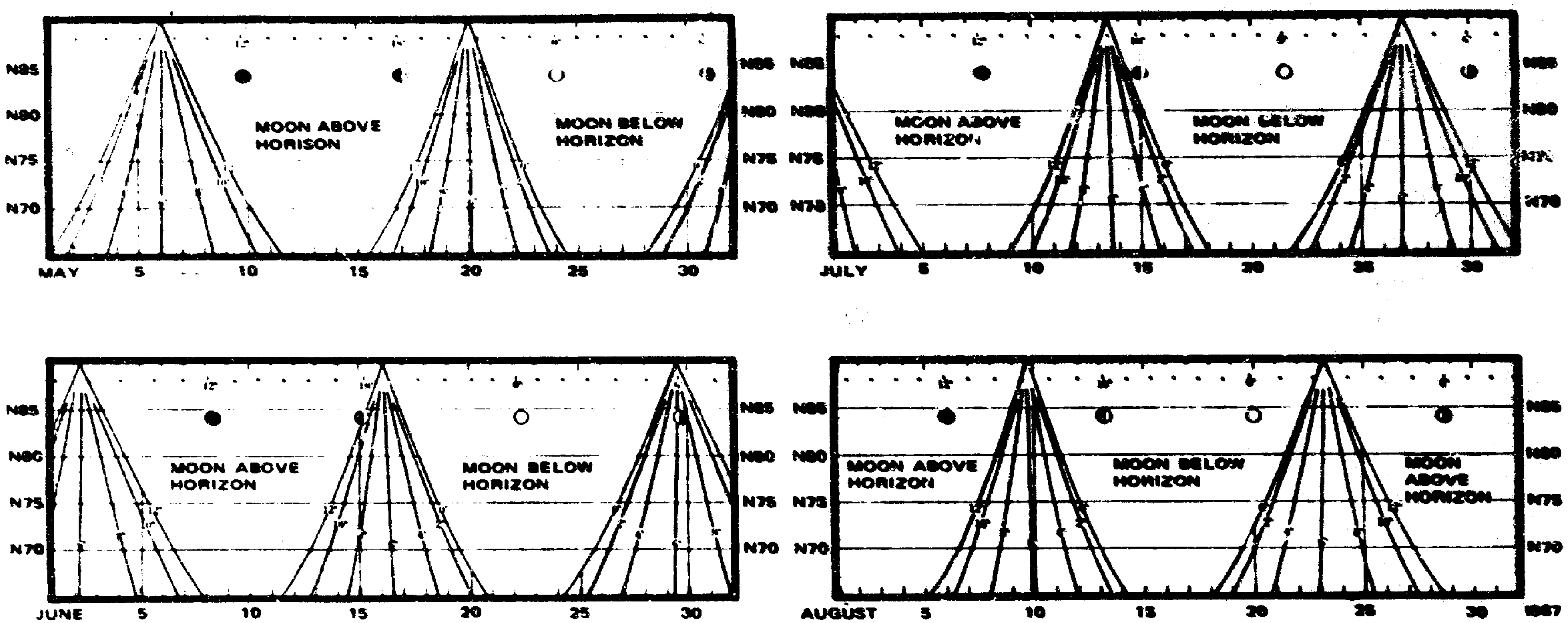


Figure 9-6: SEMIDURATION OF MOONLIGHT

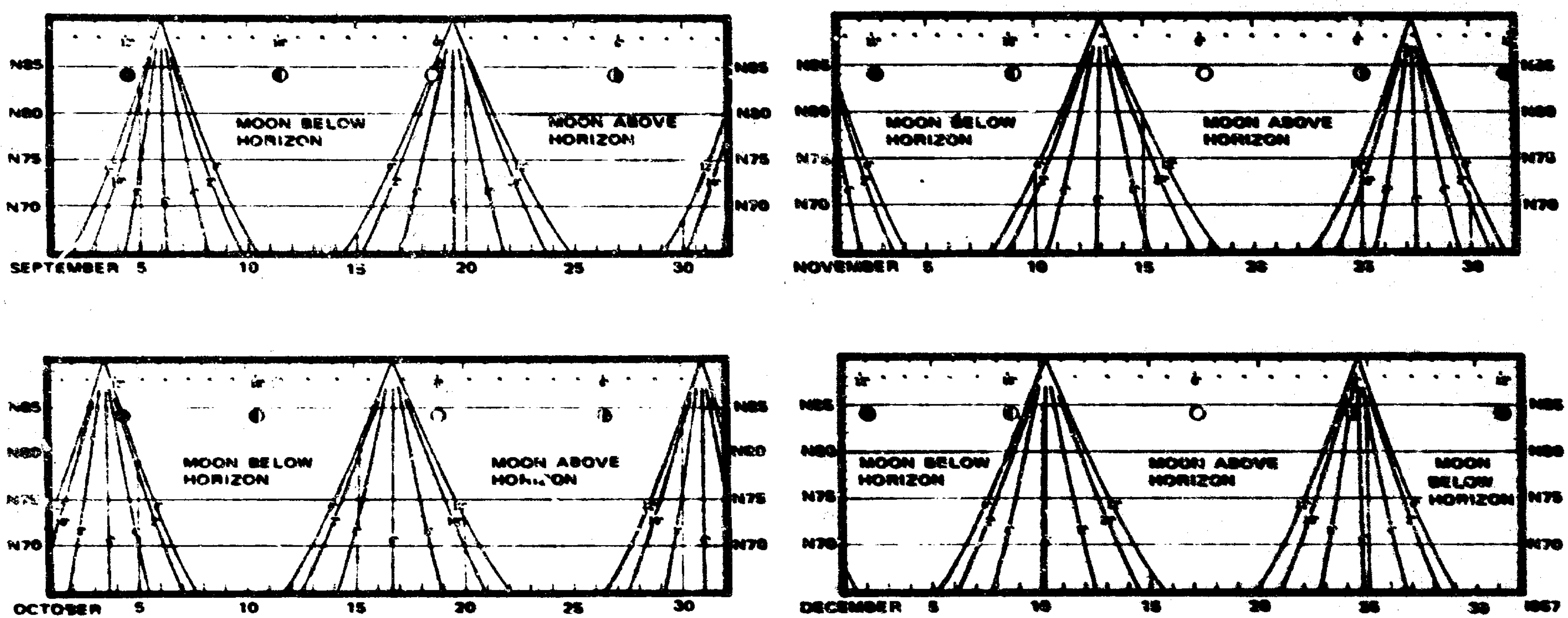


Figure 9-7: SEMIDURATION OF MOONLIGHT

Table 9-1: ALBEDO OF SNOW AND ICE

Albedo of snow and ice depending on the form and condition of surface (according to observations on Cape Sterlegov and on drifting stations North Pole NP-2, -4, -6, and -7).

Character of Surface	Character of Surface, Light	Cape Sterlegov	NP-4, -6, -7, according to Bryazgin			NP-2 according to Yakovlev		
		Average	Avg	Max	Min	Avg	Max	Min
Freshly fallen snow	Dry, clear-white, clean loose	90	88	98	72	85	95	83
Freshly fallen snow	Moist, white		80	85	80	82	88	76
Freshly fallen snow	Dry, slightly compressed		85	95	70	86	89	84
Freshly fallen snow	Moist, gray-white		77	61	59			
Storm-swept snow	Dense, dry	85	80	86	75			
Storm-swept snow	Moist, gray-white	78	75	80	56			
Dense snow	Dry, clean	80	77	80	66	76	81	72
Dense snow	Moist, gray-white	78	70	75	61	76	78	71
Recrystallized snow	Moist	72				63	73	52
Snow with ice crust (frozen snow crust)	Frozen	75				74	81	68
Snow during thaw (soaked by water)	Light-green, soiled	40-60	35		28			
Melting ice	Moist, gray		60	70	40	69	75	64
Snow and ice	Dry, gray-white		65	70	58			
Fresh-water pool in first period of melting	Light-blue water		27	36	24			

Table 9-1 (Continued)

Character of Surface	Character of Surface, Light	Cape Sterlegov	NP-4, -6, -7, according to Bryazgin			NP-2, according to Yakovlev		
		Average	Avg	Max	Min	Avg	Max	Min
Deep fresh-water pool (30-100 cm)	Green water		20	25	13			
Deep fresh-water pool (30-100 cm)	Blue water		22	28	18			
Fresh-water pool covered with ice	Smooth ice covered by ice		33	37	21			
Frozen snow crust covered by white snow	Dry					77	88	62
Ice covered by fresh snow	Dry					79	89	74

9.3 INFRARED

Interest in the use of infrared imagery to study sea ice and snow-covered terrain has been growing in recent years since far more detail of the ice structure is revealed at these frequencies than in the optical range. Thermal patterns obtained were dominated by the heat conducted from the water beneath the ice and by solar radiation. Most thermal differences were a result of differences in ice thickness, snow cover, and ice topography. Contrast between open water and ice was obviously high.

Since most of this work to date has been essentially experimental in nature, weather conditions have been generally excellent during the test flights. For this reason the effects of atmospheric attenuation are essentially unknown at this time. Pertinent to this problem are the studies that have been conducted on the heat budget of the arctic. As pointed out by Fletcher, an important difference in the arctic atmosphere and that of lower latitudes is the presence of an ice-crystal haze during the dark months. This haze grows gradually through the winter. In September the resulting attentuation of solar radiation is about the same as if water vapor was present, but by March the attenuation has doubled (Reference 4 and 5).

9.4 RF PROPAGATION

No attempt has been made in this study to obtain data regarding RF propagation characteristics on the arctic because this represents a special area of interest. Some information is available on propagation at communication frequencies and certainly at least limited operating experience is available. At radar frequencies no really useful data has been located, although it may exist in an unpublished form (Reference 6 and 7).

9.5 RADAR CLUTTER

Radar clutter measurements over the arctic ice pack are apparently nonexistent although the existence of some measurements over snow covered land has been reported. Clutter measurements over open water have been reported by many investigators, but these are without exception difficult to utilize in a practical manner due to lack of definitive sea state measurements with which to correlate the data.

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The following papers generally relate to the use of IR and radar over sea ice.

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